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APPLICATION OF FRACTURE PREVENTION PRINCIPLES TO AIRCRAFT

REPORT OF

THE COMMITTEE ON
APPLICATION OF FRACTURE PREVENTION PRINCIPLES
TO AIRCRAFT

NATIONAL MATERIALS ADVISORY BOARD
Division of Engineering — National Research Council

Publication NMAB-302

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February 1973

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PREFACE

At present, considerable activity in the area of fracture prevention principles is underway in Air Force systems, research organizations, and areas of the Department of Defense involved with materials and structures. Because of this intensive activity the Department of Defense (DOD) requested the National Materials Advisory Board (NMAB) to study the application of fracture prevention principles to aircraft.

To conduct this study the Board appointed the Committee on Application of fracture prevention principles to aircraft. Committee members and liaison representatives included both individuals with full-time aircraft system responsibilities and materials and structural sciences specialists from government, university, industry, and research organizations with broader based or different materials and structures experience than that of the aircraft specialists. This balance was deliberate to provide a wider viewpoint than that of aircraft or material specialists alone.

A critical review of all current activities was beyond the scope of the Committee's charter and, undoubtedly, would have been obsolete when completed. Consequently, the Committee limited itself to the objectives stated herein. To meet its objectives, the Committee reviewed the current state of the art. This was accomplished by subdividing the Committee into two Panels -- one on Aircraft Applications and the other on Fracture Technology, as noted below. The major portion of this report, based on information collected up to June 1972, was prepared by the two Panels, subsequently reviewed and integrated by the Committee. The Conclusions and Recommendations were derived from the written state-of-the-art reports and succeeding discussions.

Although this report presents the consensus of the entire Committee, it does not necessarily represent complete agreement on every detail. Since the state-of-the-art reports are related intimately to the conclusions and recommendations, they are appended to the report. Their contents may interest those readers attempting to obtain a brief introduction to the field; however, they are not intended to serve as a complete and detailed textbook on the matters discussed.

The report was written for a specific audience of airframe designers and materials specialists who are attempting to incorporate fracture mechanics into aircraft production.

The membership of the panels was as follows:

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ABSTRACT

The elements of current fracture control plans and associated technologies are reviewed. The specific elements are requirements and criteria, materials, design and analysis, test, manufacturing (fabrication and quality assurance), and service life (safety, durability, and risk assessment). The fracture-related technologies are fracture toughness, subcritical crack growth, metal improvement, and nondestructive evaluation (NDE). After reviewing the status, applicability, and potential of the above elements and technologies, it was concluded that fracture control plans and development of the related technologies not only afford an opportunity to reduce catastrophic failures of aircraft structures and structural maintenance but also can help to quantify many structural material, design, NDE, and maintenance decisions that now are made on a relatively qualitative basis. If the criteria selected for a fracture control plan are overly pessimistic, it is possible to add significant cost, weight, and complexity to an airframe. The Committee recommends careful trade-off studies, together with caution and flexibility, in the use of existing criteria and prior to the issuance of new criteria. The assumptions regarding initial flaw size and the requirements for analysis, testing, and NDE can have particularly serious impact.

Required technologies to implement fracture-control plans need extensive development, particularly fracture-toughness characterization of structural sections that are too thin for plane strain to apply. Also, fracture analysis under complex conditions of loading and environment presents difficulties and excessive dependence on empirical testing. Although NDE practices and techniques appear highly sophisticated and broadly based, they have serious deficiencies that must be overcome to permit using NDE in a quantitative engineering way as an integral part of the fracture-control plan.

Specific recommendations and needs for research and development for the fracture-related technologies and design applications are summarized. Based on many Committee discussions, metal improvement and quantification of the material selection process stand out as areas of maximum payoff.

I. SUMMARY CONCLUSIONS AND RECOMMENDATIONS

A. Summary

As a basis for its recommendations, the Committee on Application of Fracture Prevention Principles to Aircraft reviewed the elements of current fracture-control plans, the technologies involved, and the potentials for application of the technologies to aircraft systems. The specific elements defined were requirements and criteria, materials, design and analysis, test, manufacturing (fabrication and quality assurance), and service life (safety, durability, and risk assessment). The fracture-related technology areas that were given major attention by the Committee were fracture toughness, subcritical crack growth, metal improvement, and nondestructive evaluation (NDE).

The status, applicability, and potential of the fracture-control elements and the fracture-related technologies were reviewed. The Committee has concluded that fracture-control plans and development of related technologies afford opportunities to reduce catastrophic failure possibilities of aircraft structures and structural maintenance. In addition, opportunities exist to quantify beneficially many of the structural material, design, NDE, and maintenance decisions that now are made on a more or less qualitative basis. However, depending on the criteria selected for a fracture control plan, it also is possible to add significant cost, weight, and complexity to an airframe while precluding the use of structural configurations that generally have been satisfactory. While this effect cannot be assessed yet, the Committee recommends extreme caution,

flexibility, and careful trade-off studies in the use of existing criteria, prior to the issuance of new criteria. The assumptions regarding initial flaw size and the requirements for analysis, testing, and NDE can have particularly serious impact.

The technologies that are required to implement fracture control plans need extensive development. Fracture toughness characterization of structural sections, too thin for plane strain to apply, and fracture analysis under complex conditions of loading and environment present many difficulties and excessive dependence on empirical testing. Although NDE practices and techniques appear to be highly sophisticated and broadly based, they have serious deficiencies that must be overcome before NDE can be used quantitatively as an integral part of the fracture control plan.

Specific recommendations and needs for research and development in fracture-related technologies and design applications are summarized here and discussed at greater length throughout this report. In view of Committee discussions, it appears that metal improvement and quantification of the material selection process are areas offering maximum benefit.

B. General Conclusions

1. Although fracture control plans and fracture mechanics analyses are recent formal contractual requirements for Air Force aircraft, methods of preventing fatigue and stress corrosion cracking have been part of the structural design and development activities for more than two decades. Traditional methods were based on the properties of "sound" (unflawed) material. The fracture-control plans and fracture-mechanics

analyses that recently were introduced as formal contractual requirements seek to control initial flaw size and material properties that affect the growth of preexisting cracks. Classical linear elastic fracture mechanics offers methods for designing against crack extension in relatively heavy sections under well-defined and simple states of stress. However, extensions of linear elastic fracture mechanics may provide opportunities for improving design processes, analysis, and material selection for thinner sections and complicated loading. Significant gains in alloy development for both heavy and thin sections may be achieved by stressing fracture and fatigue characteristics instead of emphasizing static strength alone.

2. In the overall systems area, the development of fracture control plans could integrate fracture considerations into the total airframe analysis, design, fabrication, quality assurance, test, and maintenance spectrum and be beneficial in more nearly quantifying material selection, NDE, structural maintenance, and various design parameters that are now relatively qualitative.

3. Nondestructive evaluation procedures that are effective, efficient, and economical must be developed because NDE is:

a. necessary to reveal small flaws upon which fracture mechanics is based;

b. of prime significance in ensuring flight safety; and

c. the technology base of "quality assurance" that is a major cost item in fabrication and maintenance.

4. Adoption of untried or unrealistic criteria in fracture-control plans could not only increase costs appreciably

but also degrade aircraft performance by increasing weight and size to satisfy requirements. Technical criteria that do not penalize weight, cost, and performance of the aircraft unnecessarily are needed.

C. Specific Conclusions and Recommendations

1. Fracture Toughness. Fracture-toughness characterization of the specific lot of material to be used is essential for any fracture-control plan. K_{Ic}* is meaningful for thick sections only and can be determined at a significant cost. Meaningful, but simple, tests must be developed to measure fracture toughness of a material that is too thin or too tough for K_{Ic} to be measured or applied. The metal supplier should be able not only to measure fracture toughness in a simple, inexpensive way but also to control it within limits for all practical criteria. The high cost of fracture-toughness testing justifies continuing effort to devise less expensive methods of measurement.

Recommendation

Financial and technical support are recommended strongly to develop standardized low-cost methods of fracture-toughness characterization of commonly used aerospace materials in the thickness range of their applications.

2. Subcritical Crack Growth. Test specimens, frequencies, environments, and load spectra must be standardized to correlate the work of investigators in the field of cyclical crack growth. The environmental aspects are important, particularly for aircraft applications. Standard environments must be developed to approximate normal aircraft usage.

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* K_{Ic} = the plane strain crack toughness and is a material property.

Methods for the use of basic material crack-growth data are needed urgently to compute the cyclical crack-growth effects of spectrum loading accurately.

Recommendation

Fundamental research is recommended to improve the understanding of mechanisms of cyclical crack growth with emphasis on material, geometrical, and chemical factors and to provide design rules for practical problems.

3. Metal Improvement. Until recently, high static strength was the primary objective in developing the high-strength metallic alloys widely used for aircraft. The resultant data on fracture, fatigue, stress-corrosion, and subcritical flaw-growth characteristics were a beneficial bonus but not the incentive for material improvement. Unfortunately, the emphasis on materials with high ultimate strength led to materials (e.g., 7079-T6 aluminum alloy) that were susceptible to stress-corrosion failures in service use. For critical applications, the goal in material development is to improve fracture properties, fatigue, and subcritical flaw-growth characteristics in operating environments without significantly lowering the mechanical properties related to static strength.

Improvements in alloy composition, cleanliness, and processing enhance desired characteristics appreciably, as demonstrated on steels and, to a limited extent, titanium and aluminum alloys. To achieve maximum benefits while improving metal quality, a better understanding is needed of the mechanisms involved in fracture resistance and cyclical flaw growth.

The development of improved materials and their applications to optimally designed and fabricated structures affords the greatest opportunity to increase structural reliability without degrading performance and increasing costs.

Recommendation

Continuously funded research is recommended to improve metal alloy quality. The priority of research should be placed on the following in the order of listing below:

a. titanium alloys, because of their critical importance in advanced aircraft;

b. aluminum alloys, because of their relatively neglected state;

c. steels, because of their relatively advanced technological status; and

d. welded structures of the three metal systems above.

4. Nondestructive Evaluation

The establishment of a fracture-control plan requires that NDE be integrated quantitively with the vehicle design and manufacture, and NDE improvements afford the best opportunity for preventing catastrophic failures. However, many of the technologies that are required for an effective NDE program in a fracture control plan are inadequate. Where a suitable technology exists, procedures generally are not standardized and the sensitivities are not understood sufficiently. For some types of flaws such as those created during the production of a metal, NDE methods are not available presently. Improved NDE methods -- particularly methods that do not require disassembly of structural components -- are needed for use on service aircraft during periodic inspections. The cost of NDE can be a significant fraction of the manufacturing cost, and this entire area is exceptionally vulnerable to human and management problems.

Recommendations

a. Major efforts are recommended to standardize, quantify, and (where possible and economic) automate existing and potential NDE procedures.

b. The development of new NDE methods to cope with difficult and costly problems of inspecting aircraft parts and assemblies for flaws in a service environment is recommended.

5. Test. Prior to fracture mechanics, full-scale static and fatigue tests had one nominal definition of the test article with a manageable number of test conditions selected on a proven analytical basis. In fracture-mechanics considerations, the possible variety of test articles (as defined by flaw size, type, and location) is infinite. The critical conditions are not necessarily clear and the technical difficulties in fabricating a precisely flawed test article are formidable. Also, full-scale testing appears economically and technically infeasible.

Recommendation

A careful, systematic approach to simple element and component testing is recommended to utilize static and fatigue articles to measure and verify stress levels and to rely on existing or additional simple tests to validate a selected portion of the analysis.

6. Fabrication. To a large extent, flaws are inherent in a structure and result from technical and human deficiencies in the material and airframe manufacturing processes. The human element is of equal, and sometimes greater, importance than the technical element.

Recommendations

a. Intensive support of manufacturing technology in the areas of metal removal, hole generation, metal joining, thermal processing, and chemical processing is recommended. Basic objectives should be the elimination of manufacturing induced flaws and rapid automated detection of flaws when present.

b. Psychological studies are recommended to improve worker motivation.

7. Service Life Estimation (Safety, Durability, and Risk Assessment). Accurate service-life estimates for airframe structures are necessary to achieve an effective fracture-control plan. To a great extent, deterministic approaches represent merely the first step in solving problems that are inherently statistical and, apparently, these approaches are being applied to many of the phenomena in service life estimation.

The statistical aspects of NDE processes and the statistical variability of the physical processes associated with manufacturing are of fundamental importance.

Recommendation

Further research is recommended to develop the statistical characteristics of all factors involved in fracture-mechanics-based damage accumulation and life-prediction methods (reliability-risk-analysis procedures).

8. __Design and Analysis__. The practical application of fracture-prevention principles to the complex designs of aircraft structures appears exceedingly difficult even if the problems can be solved for simple structural elements (see Section III-B-3, pages 24 to 35.

__Recommendations__

a. Configuration and structural element-development programs are recommended that promise crack arrest under dynamic loadings or provide innovative means for signaling dangerous flaws.

b. Analytical methods should be developed for flaw-growth analyses around practical structural details (open holes, hole-fastener combinations, fillets, section-change areas, etc.) for both plane-strain and plane-stress conditions. Cumulative flaw-growth procedures should be developed for various conditions of load-spectrum ordering, sustained stresses, and environment.

II. INTRODUCTION

As a result of premature structural failures of several recent Air Force aircraft in service and tests, all aspects of structural criteria, analysis, design, and testing have been undergoing intensive critical review. To obtain a better perspective of the applicability of fracture mechanics to aircraft, the Department of Defense (DoD) requested the National Materials Advisory Board (NMAB) to address the issue. NMAB appointed the Committee on Application of Fracture-Prevention Principles to Aircraft to conduct the study and to:

1. assess the status, applicability, and potential of the latest concepts of fracture control for the design and utilization of advanced aircraft (airframes);
2. define a practical research and development program that should be undertaken to clarify any issues and enhance these concepts;
3. elucidate the elements of a program for fracture control to check premature failures of aircraft structures.

Although high-strength composite materials are of increasing importance in primary aircraft structures, this Committee limited its activities to metallic materials.

As part of the corrective action for one aircraft, fracture mechanics was used extensively to evaluate material characteristics and to quantify proof-testing results along lines similar to those used previously for space-vehicle pressure vessels. In this methodology, the presence of flaws, too small to be reliably detected, is postulated. As an

outgrowth of these system problems a "fracture-control plan" is a requirement in each current major Air Force system and is being incorporated as a requirement for future systems in a structural-integrity-requirement document now being prepared. These plans use fracture-mechanics analyses and related material and element testing in an overall plan to preclude catastrophic failures from initial or service-induced flaws that cannot be found by current pection techniques. The use of fracture control pl as not limited to Air Force vehicles. Commercial transport aircraft have used similar principles for over a decade. A fracture-control plan will be utilized for the NASA space shuttle and for future Navy aircraft systems.

The term fracture-control plan is used extensively in this report,but it is not a replacement for present structural design and validation procedures. The fracture-control plan, with the exception of an initial flaw assumption, merely extends and, in some cases, quantifies elements already revehicles, and similar principles have been applied to commercial transport aircraft for over a decade. A fracture-control plan also will be utilized for the NASA space shuttle and for future Navy aircraft systems.

2. material selection, control, and evaluation testing,
3. some aspects of structural design and analysis, and
4. inspection and maintenance.

The elements of fracture-control plans are discussed in pages 19 to 46 and 57 to 98. The unique aspect of the fracture-control plan is simply the introduction of initial flaw

assumptions and fracture considerations into all these activities together with the integration of NDE with the design and analysis criteria.

III. AIRCRAFT APPLICATIONS

A. Introduction

1. Nature of the Problem

The problem of fracture of metallic structures is long standing and well documented in the historical engineering literature. Failures have occurred in static structures subjected essentially to sustained loads and in multifarious vehicles whose loads are primarily randomly variable. However, in recent years, fracture has become a more acute problem that has been induced fundamentally by the desire for increased aircraft performance. The desire to achieve increased performance has resulted in efforts to increase structural efficiency (i.e., reduce the structural weight fraction), while simultaneously imposing other stringent design requirements (such as operating at higher dynamic pressures and temperatures) that provide longer service life and fit the structures into a severely limited physical envelope.

To cope with this design challenge the designer has resorted to higher-strength metallic alloys and tended toward the monolithic-type structural configuration to attain high levels of structural efficiency. In so doing, materials have been specified and used that have high ultimate and yield strengths and, as a consequence, generally low fracture toughness. At the same time, with the increased design operating-stress levels, critical crack sizes have become significantly smaller and crack propagation during service has become more rapid. In a typical case involving high-strength steel alloys, if a flaw is present, a 25 percent increase in material strength and operating stress will reduce the residual strength by approximately

50 percent, as compared to the original material. Also, the lower stress-corrosion resistance of these higher strength materials has accounted for a significant number of service difficulties in parts subjected to sustained loads or residual stresses resulting from improper design or manufacturing processing. While the designers were aware of the less desirable fracture characteristics of high-strength materials, their choice of materials was based primarily on the desire to achieve other stated design objectives in the absence of specific quantified fracture-mechanics requirements.

The manufacturing aspects associated with these higher strength materials also have contributed to the problem because a flaw-free article is more difficult to produce in harder materials that require more precise machining and processing methods. In addition, previously acceptable quality-assurance procedures often are inadequate for reliable detection of the small flaw sizes that are significant in these lower tolerance materials.

Paradoxically, the engineer's increased ability to perform more exact and precise structural analysis with the aid of improved load-prediction techniques and finite element-computer analysis also may have contributed to the problem. These more refined analyses encouraged the designer to use more rational design criteria and eliminate arbitrary factors. Therefore, margins of safety built into the structure are lower but more uniform than those previously used when the uncertainties of the analytical procedures required conservative assumptions.

Despite the publicity some recent difficulties in service aircraft have received, a proper perspective on the relative

significance of aircraft structural problems should be maintained. While it is extremely unpalatable to lose any aircraft because of catastrophic in-flight structural failure, such losses represent only a small percentage of the total losses that occur for all causes. Available accident data indicate that structural failures are responsible for approximately one percent of USAF fighter-type aircraft losses or, stated in terms of flight time, approximately one loss per million hours of flight time. The total losses of all types of USAF aircraft are approximately half this rate, and commercial transport aircraft losses are believed to be even smaller. Furthermore, for an accurate picture using aircraft loss statistics, a detailed assessment of each individual case must be made to determine whether the cause, while structural in nature, may be attributable to other factors, such as overload or damage to the structure, that are unrelated to the design or materials used.

Although catastrophic failure (loss of aircraft) attracts the most attention, it is not the only structural-failure problem; those associated with maintenance of the airframe structure also are of major concern. These maintenance problems are not evident from examination of accident statistics, but they result in exorbitant costs, aircraft out-of-service, and a reduced national-defense capability in the case of military aircraft.

Another facet of this problem is that the structural reliability and/or flight risk can be assessed only on a statistical basis since each influencing factor on the life of the structure has statistical variability. This assessment includes the applied loads that are dependent upon service usage,

material properties, manufacturing processes, and quality-assurance procedures. Therefore, quantifying the problem in simple terms is difficult and is a frustration to those looking for unequivocal answers. At present, acceptable reliability and/or flight risk have not been defined clearly, and there is no obvious universal answer. The requirements imposed on a single-place-fighter aircraft should be different than those imposed on a transport-type aircraft. To quantify the total problem, these requirements need to be established and understood.

2. State of the Art and Current Practice

In the past, the application of fracture-prevention principles to aircraft design generally has been limited to materials selection and design measures intended to mitigate fatigue damage. The quantitative data that were pertinent to fracture and used in material selection were Charpy impact test results and values of plane-strain fracture toughness obtained from simple test specimens. The qualitative information used was the accumulated experience on the same or similar materials. Successful application of concepts of linear elastic-fracture mechanics to explain test and in-service failures led to their utilization as a tool in preventing fracture occurrences, an application gaining acceptance in the aerospace industry. More recently, as a result of numerous test and service difficulties with aircraft using high-strength materials, greater attention has been given to designing with high-strength material and to selecting material to provide airframe structures with greater tolerance to fracture. However, until very recently, the design-decision process involving these materials has been more qualitative than quantitative, i.e., comparison of K_{Ic} values

and selection based on higher numbers or acceptance of fail-safe design concepts. Fundamental fracture-prevention principles are well established, but a specific technical discipline has emerged only in the last few years. Presently, extensive research and investigative effort are underway in government agencies, academic institutions, and industry. In fact, the proliferation of generated data is so great that it is difficult to assimilate and organize them in a useful way to cope with real design problems. The situation is complicated by the multitude of involved technical disciplines; in addition to the usually considered engineering disciplines, such as metallurgy, structural analysis, and design, the fundamental physics of materials also are included as are manufacturing and inspection technology.

Both the Air Force and NASA have made concerted efforts to define the problem and develop research and development programs, directed toward both short- and long-term solutions. Two Air Force Flight Dynamics Laboratory publications (Wilhelm, 1970; Wood, 1971) aim at providing useful information for design purposes, and NASA has issued several reports resulting from ad hoc committee findings on the subject (NASA, August 1971; NASA, October 1971). As previously noted, a large quantity of data is being generated, and these reports are only indicative of the effort in this area.

As a result of several laboratory-test failures and an in-flight primary-structure failure, the F-111 program quantified and used fracture-mechanics analysis to establish fleet-inspection intervals and inspection requirements. The USAF F-15 program employed fracture-mechanics input analysis

advantageously during the initial production state in a program somewhat similar to that used for the F-111. The Navy F-14 program employed specific design objectives in the titanium-welded structure to assure uniform fracture properties in the parent- and weld-zone areas. To date, the most extensive and comprehensive fracture-control program developed has been instituted on the USAF B-1.

In summary, advancing requirements for aircraft performance are inducing designers to use fracture-sensitive materials when the necessary information in terms of data bank and analytical and experimental methodology is inadequate for their reliable use.

3. Objectives

The objectives of applying fracture-prevention principles to the design of aircraft, in general terms, are to reduce the loss rate due to catastrophic fracture in future aircraft systems below the present rate, to minimize the cost of maintenance, and to reduce the number of aircraft that are out of service for repairs necessitated by fracture occurrence.

From the designers' viewpoint, an obvious solution to brittle-fracture problems would be the development of materials with sufficient toughness to preclude plane-strain failures and with such low crack-propagation characteristics (in both cyclic and sustained loading) and manufacturing- or service-induced cracks would not grow to catastrophic size during the service life of the aircraft. Since this goal does not appear realistically attainable in the foreseeable future, the problem must be approached on a broader front. Design techniques must

be developed to provide structural arrangements that are inherently damage tolerant. These techniques, combined with better informed material selection and NDE procedures, must be integrated into a comprehensive fracture-control plan including improved manufacturing processes and quality-assurance practices as well.

It is believed that considerable progress could be achieved by establishing design requirements specifically recognizing fracture problems. The present situation is comparable to the general problems of fatigue of an earlier period. In the last decade, significant strides were made once requirements were quantified and incorporated in design, test, and manufacturing. A necessary step in achieving a working fracture-prevention plan is the quantifying of requirements, particularly specification of acceptable failure rates that must be met by new airframe systems.

B. Elements of Fracture Control

As a result of the awareness of the fracture problem, increasing emphasis is being placed on developing specific programs, such as those on the F-15 and B-1, to systematize and quantify the fracture-mechanics design and analysis effort. There is no generally accepted fracture-control program procedure; however, a typical program should address the following elements:

1. requirements/criteria;
2. materials;
3. design and analysis;
4. test;
5. manufacturing (fabrication, quality assurance); and
6. service life (safety, durability, risk assessment).

No ordering of priorities is intended in this listing. Indeed, a successful fracture-control program will include all these interrelated elements. Each individual element is reviewed briefly in the paragraphs below.

1. Requirements/Criteria

In the past, no explicit design requirements/criteria pertaining to fracture have been specified contractually. The B-1 program is the first to implement specific requirements at the beginning of a contract. These requirements are based on the essential premises that all critical structures contain flaws of a minimum specified size and that the time for these flaws to propagate to failure must be greater than a specified inspection interval that depends on the structural concept employed and the *in situ* inspectability of the part. These requirements assume that:

a. All critical parts and locations within a part can be established.

b. A high degree of confidence exists in the flaw-detection capability.

c. Crack propagation and residual strength can be analyzed within reasonable accuracy.

These assumptions are enumerated to emphasize the significant points and agreements that must be established to permit the designer to use the criteria.

A more general set of requirements also has resulted from the efforts of the Air Force Committee established to update the Aircraft Structural Integrity Program (ASIP) document and related structural-design MIL specifications. This set of requirements was developed over several years; it was guided by the Air Force Laboratories at the Aeronautical Systems Division

(ASD) at Wright-Patterson Air Force Base and was supported by industry and other government agencies.

This effort is documented in a proposed MIL specification that integrates fracture-mechanics considerations into the total Air Force structural-integrity program. The Navy is also revising its basic aircraft-design specification to include requirements that consider fracture during design and as an integral part of the structural integrity-design program.

The calculation of service life of flawed structures requires a more specific definition of the service usage and environment than has been required previously for calculated service life under fatigue; therefore, specific requirements must be developed and stated. Essentially, this definition and the resulting requirements must be derived statistically and can vary widely for different type aircraft and even within a given series of aircraft. When computing crack propagation, environmental factors such as temperature and the presence of humidity, water, fuels, or other chemicals must be considered, in addition to establishing the load and, subsequently, stress history of an individual part required for the usual fatigue analysis. This environmental consideration is particularly important in structures that employ materials with a high susceptibility to environmental conditions. For example, the crack-propagation rates of high-strength martensitic steels may differ as much as an order of magnitude between dry air and water.

The consistency of requirements within involved government agencies is viewed as a major problem. Also, much additional effort is needed to expand the basic requirements into a usable set of detail-design criteria. To a great extent, practical

experience gained in designing to specific requirements, such as in the B-1 program, will determine the development of future criteria. Historically, structural-design specifications have been revised frequently to reflect advancing technology and current experience, and fracture-mechanics requirements probably will evolve in a similar manner.

The criteria for evaluating tests are as important as the design criteria discussed above. Obviously, these test criteria have a significant impact on program aspects, since within the currently understood framework of fracture-mechanics technology, complete validation of the design would involve running innumerable tests to cover all critical areas of each critical part. This testing probably could not be accomplished within the usual schedule constraints placed on research, development, testing, and experimental programs. Apparently, compromise in this area and some analytical assessments will be necessary instead of complete testing to qualify or certify the design. Careful consideration must be given to the significance of cost, schedule tracks between test and analysis, and the confidence level resulting from compromise in these areas.

a. Required Research and Development

Valid fracture-design criteria, consistent with minimum weight/cost objectives, must be established by assimilation of test data and past experiences with structural concepts and should include:

(1) initial flaw-size assumptions as a function of statistical behavior, material, nondestructive evaluation, and/or proof test;

(2) definition of service environment including corrosive elements, thermal exposures (including extremes), cyclic load histories/frequencies, and steady-state load histories; and

(3) scatter factors applicable to flaw growth to account for material, manufacturing, and service variables.

2. Materials

Obviously, the classification and characterization of materials is a necessary element of a fracture-control program. A major problem in material characterization is the standardization of test specimens and development of procedures to obtain valid, directly comparable fracture-mechanics data for the various materials being considered. ASTM Subcommittee E-24 is addressing this subject on a continuing basis. The importance of establishing consistent, directly comparable material data is essential to the materials development program, as well as to design, so that solid benchmarks can be used to measure materials technology development progress.

Basic fracture-mechanics data that are required to perform a fracture analysis must be obtained for all selected materials for use in the design. The required basic data are fracture toughness (K_{1c} and K_c), crack-propagation data (da/dN), and the stress corrosion threshold level (K_{Iscc}).

The crack-propagation rate was found to be a function of the stress range and ratio, environment (temperature and chemical), and load frequency and sequencing. Further, an interrelationship depends upon the combination of these conditions. Crack propagation data usually were obtained by running constant amplitude tests. However, random spectrum loading was observed

to cause retardation of crack growth in certain materials by factors of as much as 6 to 10. This observation placed increased emphasis on running random spectrum-type tests. Retardation effects also are influenced by the existing environment, and these environmental/spectrum interactions must be determined. Accordingly, a complete fracture-mechanics data program is very large and indicates the need to develop a consistent and usable data bank.

The original fracture-mechanics efforts were directed to relatively simple structures, such as pressure vessels, and to flaws in plate-type structures. In aircraft, however, fatigue cracks that may occur in service as well as flaws that may exist in the basic material or may be generated as a result of the manufacturing process also must be considered. The service-induced crack that occurs at stress-concentration points, such as bolt holes and machined notches, or results from combat damage presents a more complex situation because the stress state of the material in the immediate vicinity of these areas may be beyond the material's elastic limit and, therefore, beyond the applicability of linear-elastic fracture-mechanics analysis. The fracture-mechanics data test program must include these features of the design.

Material aspects of the problem are covered elsewhere in this report.

3. Design and Analysis

In this discussion, design is defined as the process of creating design concepts and establishing the detail configuration of structural components and elements, including materials selection and supporting and substantiating analysis.

As one of the elements of fracture control, the design process involves the application of judgment and the interjection of practical experience. Present refinements of analytical methods, such as finite element analysis and fine grid-stress analysis, have tended to reduce the risk associated with the involved judgment factors and provide better balanced structural configurations.

However, considerable latitude is available in selecting the structural concepts. In the past, when fracture has been considered, these concepts generally have revolved around the question of whether a fail-safe or a safe-life type of structure should be used. The possibilities of including design features that may arrest, or reduce, flaw growth have been considered only recently. In effect, a fail-safe structure does imply crack arrestment, i.e., failure confined to one element of a multi-element load path. In addition, an appreciable reduction in strength is generally implied and is tolerable for a short period. Therefore, a distinction exists between a fail-safe design and a structural design that employs crack-arrestment or retardation features to enable a structure to perform without significant degradation of strength or service life even though flaws may propagate up to the point of arrestment.

Generally, the structural portions of the aircraft's airframe employ a large number of discrete elements, such as bulkheads, spars, ribs, and load-carrying covering. In most of these elements, some degree of tolerance to damage does exist whether planned or not. Further, there has been a trend toward including structural redundancy in the design even though particular requirements for fail safety may not be specified.

This redundancy is employed particularly for the aerodynamic surfaces where multiple spar configurations are commonly used. The fuselage portion of the structure also usually has a degree of redundancy due to symmetry about the vertical centerline. In the past, these factors have been important in preventing catastrophic failures although failure of individual structural elements did occur.

While fracture-prevention principles must be applied in some degree to all elements of the structure in the design process, obviously emphasis must be placed on those structural parts whose failure would cause catastrophic damage or, in the case of redundant fail-safe structures, would cause a large reduction in residual strength. While in some cases a simple examination of the structural configuration is sufficient to ascertain that failure obviously will be catastrophic, much more elaborate and extensive failure-analysis methods must be applied in the majority of cases.

In the material-selection process, where fracture-mechanics characteristics are concerned, considerations generally are qualitative rather than quantitative. Emphasis is given to other material properties of interest in designing a structure for minimum weight. During the past 10 years, fatigue life was an important consideration in selecting structural materials, but virtually no consideration was given to crack-propagation aspects *per se*. Unfortunately, a material that has good overall fatigue properties will not necessarily exhibit slow crack-propagation rates. Fracture-prevention consideration must be a factor of equal importance in material selection in the future.

An additional fracture-prevention factor, which is directly a function of design, is the inspectability of the structure in the final assembled configuration. This facet of the fracture-control program is hard to overvalue. The frequent visual inspection of critical components by operating personnel is invaluable in avoiding catastrophic fracture occurrences.

Analytical methods currently used in fracture-control programs, basically are deterministic. Occasionally, their complexities are disquieting when the relative accuracy of the empirical data that they manipulate is considered; however, they are the best of a poor lot of alternatives and the only tools available for the time being.

To perform a fracture analysis effectively, all elements of the fracture-control plan must be considered. The basic methodology of computing crack growth and critical crack size is complex due to the many variables that enter into the computation and the use of high-speed digital computers is required. To limit these problems to a reasonable size, engineering judgment must be exercised in selecting the particular points within structural components and elements that will be analyzed. This judgment must be based on an experienced insight into the total fracture-mechanics problem and on more detailed knowledge of stresses within the part than that required for static-strength assessment or fatigue analysis.

In the past, fracture-mechanics analysis generally dealt with relatively simple crack models, such as the part-through semicircular crack in a simple uniaxial stress field. Usually, the cracks that develop in service involve stress concentrations.

A large number of unique stress-concentration conditions, such as bolt holes, machined stiffened runouts, ribs, bosses, lugs, and interference-type fasteners, must be considered in a typical design. More complex test specimens are being employed because either the analytical procedures for solving this problem or the budget to perform analyses, which are technically feasible but very costly, is inadequate. These tests are both time-consuming and costly and still may not be representative of the complete structural situation.

While some fundamental fracture-mechanics equations are based on theory and have been used successfully for the simple flaw models, other equations (i.e., subcritical crack growth) depend entirely on empirically obtained relationships. Current analytic methods are based essentially on these empirically derived data and must be updated continually in the same way as the material-properties data bank. Until adequate theoretical explanations are produced for observed fracture phenomena, and until experimental results based on this theory are reproduced consistently, analytical results must be treated conservatively and whenever possible, verified by tests. Three types of information are needed to characterize materials and to apply quantitative fracture-mechanics analyses in its present state:

a. a lower bound value of the fracture-toughness parameter, K_{Ic} or K_c;

b. reliable values for the crack-growth parameters, da/dN or da/dt; and

c. the lower limit of detectability by NDE of a flaw or crack.

a. Fracture Toughness

Important questions about the characterization of fracture toughness concern:

(1) the suitability of the K_{Ic} or K_c measurement itself as the best criterion of fracture toughness;

(2) the standardization of test specimens and procedures; and

(3) the definition of the lower bound value best suited to the analysis in question.

Considerable visibility has been given recently to efforts (e.g., those of the ASTM Committee E-24) to adopt uniform test criteria and data-analysis methods. While much remains to be done, significant progress has been made. The relatively recent upsurge of interest in fracture mechanics as a design tool and the increased uniformity of test methods have resulted in a much better structural materials data base from which to choose more acurate design values. such as the lower bounds for fracture toughness, K_{Ic} and K_c, and the stress-corrosion threshold, K_{Iscc}. Concurrently, research work continues on alternate means of evaluating fracture properties, especially a method theoretically valid in the presence of plastic flow, such as the J-integral (Rice, 1968) and the crack-opening displacement (COD) measurement (BISRA, 1968).

b. Crack-Growth Measurement

The establishment of flaw- or crack-growth rates (e.g., da/dN) is required for the analysis of structural integrity and prediction of the time (or number of stress cycles) for the crack to develop to the critical size resulting in unstable growth. Commonly, crack-growth rates are

obtained in constant amplitude-fatigue tests and presented as a function of the stress-intensity range (ΔK) and stress ratio. Also, such tests are conducted under various environmental conditions, including temperature, chemical, and atmospheric conditions. Crack growth is affected generally by the strong interacting effects of operational load spectra and most structural materials exhibit a propagation-rate retardation by a factor of as much as 6 to 10. Other testing variables, such as metallurgical and microstructural variations within a specific alloy composition, dissimilar test specimens, discrepancies in stress-intensity correction factors for flaw geometry, and minor environmental changes between experiments, contribute to the scatter in data normally observed. These interacting effects establish operational life estimates that are based on the slow crack-growth interval preceding the initiation of unstable growth.

c. NDE Flaw Detectability Level (See Appendix D)

The time interval before unstable crack growth (during which slow crack growth proceeds) usually is estimated from the crack-propagation function, da/dN. When estimating a "safe" interval, an initial flaw or crack size (a_o) must be assigned from which propagation starts at time (t_o) at rate (da/dN). The assumed or measured initial size (a_o) must equal or exceed the minimum flaw size reliably detectable by NDE. Larger flaws than this minimum will result in premature failures due to their faster growth rates. Thus, the prediction of the time to reach critical flaw size depends primarily on the probability of NDE detection of small flaws. Therefore, the establishment of the lower limit of flaw detectability with demonstrated reliability (probability of

detection at a given confidence level) is a critical factor in the characterization of materials and structures and must be an integral part of design criteria containing fracture-mechanics requirements.

In the conventional design process, the designer assumes that the handbook values of tensile ultimate stress, tensile yield stress, and modulus of his materials are representative for his particular design. To establish the design stress, the handbook value is divided by a suitable factor of safety that depends upon design specifications or experience. Specifications generally require inspection of the part to reveal flaws, defects, or inhomogeneities that will cause material properties to deviate significantly from the handbook values. In this process, the designer recognizes that flaws may occur but uses NDE as a go no-go quality-control process. If no flaws are detected, the part is passed. If flaws are detected, the part is withdrawn for further examination and possible destructive testing.

The current state of the art in critical aerospace design for a safe-life structure can use a design criterion based on the concepts of fracture mechanics. This criterion permits calculation of the failure stress (σ_f) for a part containing a flaw length (2a) by the equation:

$$\alpha \sigma_f \sqrt{\pi a} = K_{Ic} \quad , \qquad (1)$$

where α is a factor associated with the geometry of the flaw and the type of part.

Generally, the initial design assumes that at the outset of its service the part contains no flaw greater than a critical size. Primarily, this assumption (at a given confidence or probability level) is made for unassembled parts or simple monolithic structures, and the role of quality-assurance (QA) personnel is to determine the limits of acceptability of that assumption for any given part. However, during assembly of the structure or subsequent aircraft structural examinations, such as inspection, and after necessary repair, additional assurance must be given that no critical flaws exist in the operating structures. Here, the emphasis is on critical flaws and flaws larger than the limits of detectability assumed in the QA inspection. The inspection for such flaws is a field inspection and usually does not allow complete disassembly of the component parts. The degree of accuracy and coverage of such an inspection is controlled by basic flaw-detection capabilities and the level of inspectability of the assembled part.

The NDE procedure must be quantified so that the NDI indication of a flaw size ($2a_{NDI}$), if detected, can be used in Equation (1) to predict the failure of the part.

The possibility of a design method, based on a nondestructive testing fracture-mechanics (NDT-FM) approach, has been verified (Packman, et al., 1969). When combined with the NDI indications of flaw size as measured by one or more tests, such as X-ray, penetrant, magnetic particle, and shear-wave ultrasonics, the fracture-mechanics formulation predicted failure loads of flawed 7075-T6511 aluminum and 4330 V modified steel to within ± 10 percent for almost all flaw sizes examined.

These fracture-mechanics design requirements demand the application of high confidence levels to the fracture toughness values and an inspection process to ensure the safety of the resulting structure at a minimum weight.

The use of a NDE-FM design criterion for critical aerospace parts places a great burden on the "limits of detectability" of the NDE technique. The exact value of the smallest flaw that can be detected with a high degree of confidence must be determined to predict the maximum flaw size that will be overlooked at a known probability and confidence level. Thus, at a given confidence level, NDE and production quality-control personnel are expected to remove all parts with flaws larger than the assumed critical size.

d. Required Research and Development

(1) Design configurations and techniques for effective crack arrest under dynamic loading conditions should receive continued development. Examples include laminated structure, brazed or bonded strips, and local structural detail.

(2) Innovations that signal imminent failure, such as leak-before-break designs, should be developed.

(3) In terms of analytical methodology regarding fracture control, the primary need is an adequate theoretical base to explain the observed diverse phenomena. A better understanding of the physics underlying fracture probably would result in more rational and consistent data collection and evaluation. This is obviously a long-term objective; however, action in this field cannot be postponed, the following near-term objectives should be pursued also

(a) Improved-flaw growth/fracture-analysis methods are needed for plane-strain and plane-stress conditions involving realistic structural detail (open holes, splice-hole patterns, fillets, etc.). Solutions are needed for both elastic and inelastic stress-field conditions.

(b) Improved procedures are needed for combined stress fields, load redistribution effects (e.g., surface flaw-to-through-thickness growth), and crack arrest.

(c) Cumulative flaw-growth procedures, based on a better physical description of flaw growth, should be developed to replace semi-empirical methods currently in use. These procedures must properly account for load-spectrum interaction (retardation), sustained stresses, and environmental effects. Creep effects on flaw growth must also be considered where high temperature is involved.

(d) Finite element solutions for stress-intensity fields, surrounding both surface flaws and flaws originating at structural discontinuities, offer considerable promise for flaw-growth/fracture-analysis and, therefore, should be pursued.

(e) Analytical methods for predicting crack initiation and transition into microscopic flaws, as a function of material, surface condition, and loading environment, should be an objective for research and development involving fatigue/fracture-analysis methods.

4. Testing

a. Discussion

The testing of structural elements and components is an essential part of the design process. Usually, development-type testing is conducted in conjunction with the design to establish confidence in the concepts and configurations under consideration and to evaluate alternate designs. In this development-test program, fracture-mechanics considerations now must be integrated into the test planning and given equal weight with other factors being evaluated.

At the present confidence level in the analytical treatment of flaw growth, it is reasonable that demonstration testing will be necessary for the more complex situations existing in critical parts. Undoubtedly, this testing will be done on a component or perhaps even a single-part basis. Since testing usually will have a large impact if the results are disappointing, it must be done with meticulous attention to environment, loading, and physical preparation of the specimen. The interrelatedness of the elements of a fracture-control program is obvious when the various features that must be considered in making a representative test of the actual hardware and its utilization are contemplated.

The qualification test program, which proves the final design and is conducted normally on major components or the complete airframe, will be affected also by the introduction of a fracture-mechanics requirement. The more usual structural qualification programs, such as static and fatigue testing, more or less involve end point tests to destruction. In the case of fracture-mechanics testing, a large number of failure-type tests must conducted if all critical elements are to

be tested. Extensive testing of this nature would be extremely costly and it is probable that a complete qualification program, involving all critical elements and critical areas within these elements, never could be conducted practically.

The testing, discussed above, is associated with the static, or slow loading, strength of the aircraft structure. The requirements of operating in a dynamic environment must be met and validated. Tests that verify analytically determined normal modes of vibration, with certain members failed, must be considered. Requirements of static aeroelastic behavior, e.g., control surface effectivity, and flutter-free operation somehow must be demonstrated. The cost of this testing must be fed back into the design decision-making process for its impact on configuration.

b. <u>Required Research and Development</u>

(1) Qualification-test programs to include damage tolerance evaluation will require procedures for developing rational fatigue-test spectra and test environments.

(2) Procedures for test-time reduction in accounting for sustained loads will be needed where sustained loads cannot be shown to have a negligible effect on flaw growth.

(3) Test procedure development must recognize load ordering, crack-growth thresholds, and frequency where aggressive environments are involved.

(3) Methods are needed for interpretation of fracture planes, particularly where random-load ordering is involved (e.g., insertion of marker bands in the loading sequence).

(5) Further research on materials categorization testing is essential to provide confidence in relative evaluations made in material selection.

5. Manufacturing (Fabrication, Quality Assurance)

a. Discussion

The total manufacturing process, including inspection, must be addressed if a complete fracture-control program is to be implemented. The correct and precise interpretation of the design rendered into hardware is essential. In the past, a significant number of fracture problems originated in manufacturing operations due to lack of emphasis on and understanding of the significance of minor defects. This situation is compounded when coupled with the general inadequacy of NDE and when dealing with high-strength metallic structures. To accomplish the objective of assuring proper manufacturing and inspection, an intimate relationship is required among the designer, the materials engineer, and the manufacturing and quality-assurance elements of the organization. Also, specific and detailed fabrication and inspection information and direction are required.

This may appear somewhat anomalous when the basic premise of current fracture-prevention programs, such as the B-1, assumes that preexisting cracks are present and the design is tolerant to this condition. However, the assumption also is made that flaws are detectable within certain limits with a high degree of reliability and, therefore, the penalties that must be incurred in the design obviously are a direct reflection of the quality of fabrication and inspection. Theoretically, if it were possible to fabricate and inspect to standards that would eliminate all flaws above the crack-propagation-threshold

level, crack growth would never occur in service from a manufactured-induced defect. However, the size of permissible defects in the areas of stress concentrations are so minute that this situation is never realized and not completely understood at this time due to the plastic strains present.

b. Required Research and Development

(1) Considerable improvement in manufacturing techniques to minimize surface damage can and should be made. An example is the use of 18 flute-carbide reamers rather than 3-flute reamers in drilling fastener holes in steel. Possibly, similar studies involving other cutting tools could lead to considerable improvement. A relative comparison of surface finishes that are produced by various manufacturing methods is available now through the use of a scanning electron microscope. The use of this tool could lead to improved fatigue and fracture performance of future aircraft by eliminating the more harmful manufacturing techniques.

(2) Improved nondestructive evaluation methods should be adapted for production as soon as possible. Each method should be accompanied by a human factors' program to characterize the NDE process in terms of probability of detection versus flaw size at a high confidence level (95 percent) under production conditions. Probability-of-detection curves are needed not only to evaluate the procedure but also for use in risk-assessment procedures.

(3) Process-control documents must be reviewed and revised on a continuing basis to assure that design levels of fracture resistance are achieved and that effective stress-corrosion control is maintained.

(4) A motivational program must be developed to increase the awareness and performance of the production worker and, more importantly, to achieve fracture control in high-strength materials.

6. Service-Life Estimation (Safety, Durability, and Risk Assessment)

a. Discussion

The establishment of accurate service-life estimates for airframe structures is among the most important, yet difficult to implement, elements of an effective fracture-control plan. Ideally, such estimates should provide a total characterization of performance with specific reference to:

(1) verification of structural integrity (safety)

(2) prediction of the expected service life under anticipated operational usage (durability) and

(3) assessment of the risk associated with such predictions (reliability).

Furthermore, the general methodology, as well as the specific procedures for providing the above characterization, should involve all phases of the structural-development cycle from materials evaluation and selection to the reliability demonstration and acceptance of a fleet of completed structures, including an appropriate inspection and maintenance program keyed to service-life estimates.

Current conventional procedures of service-life estimation produce only a partial characterization and are marked necessarily by empiricism imposed by limitations in the state of the art and experience. The establishment of static-strength margins of safety is accomplished initially by

(arbitrarily) selecting the operational limit load as two thirds (or occasionally another fraction) of the ultimate load and minimizing (or disallowing) the occurrence or exceedance of this limit load during the intended structure lifetime. Generally, structural-safety analysis, whether performed using a safe-life or fail-safe criterion, infers (statistically or otherwise) some measure of confidence that can be associated with the assumed strength margin for a group of structures. The process depends heavily upon the experimental results of component elemental development tests and does not follow a well-established or set procedure (although concepts of structural-safety analysis have been proposed for many years (Freudenthal, 1957).

Conventional procedures for estimating structural fatigue-life expectancy are based on the establishment (through appropriate structural tests) of a life "estimate" to which a somewhat arbitrarily chosen fixed scatter factor (usually ranging from 2 to 5) is applied to reduce this "estimate" to a presumably "safe" service life (Raithby, 1961; Wells and King, 1970). The size of this scatter factor usually is based on judgment or a simple probability analysis (Raithby, 1961; Butler, 1959). By its very nature, this approach deals only with the mean or "average" fatigue life, and the probability of lives shorter than this reduced "safe" operational life in an aircraft fleet is undefined and presumably ignored. Historically, this type of fatigue-life estimation process has been applied principally to cases where only total life to a predefined failure is important and directly measurable in conventional fatigue tests without regard for the instantaneous rate of damage development (e.g., da/dN). The estimation of life that is based on a projection from crack-growth rate, introduces new complexities in the otherwise

relatively straightforward analytical experimental situation. Further, an experience base for aircraft structural design and durability characterization, using a fracture-mechanics model, is essentially nonexistent. The methods are described elsewhere in this report.

Contributing to the complexities of using a fracture-mechanics model for fatigue-life prediction are various facts including:

(1) Life estimates are subject to error since observed crack-propagation rates (da/dN) at specific values of the stress-range intensity factor (ΔK) show as much scatter as fatigue lives at specific values of the stress amplitude in conventional fatigue tests.

(2) On the same metal, a scatter range of at least 1:3 in observed crack-propagation rates must be anticipated, while crack-propagation rates in the same class of metal may vary still more.

A similar uncertainty applies to the determination of the critical crack size. The rate of slow crack propagation is not a simple power function of the (constant) stress-range intensity factor (ΔK), as is assumed usually, but deviates significantly from such a function at both ends of the ΔK range. The shape of this function is not known for variable stress-range intensities (ΔK) either without or with constant or variable mean-stress intensity. Further, in view of the severe interactions between high and low intensities that are due mainly to residual stress fields at the crack roots, additional uncertainty arises from attempts at super-position of such rates at variable stress-range intensities. These interactions also may reduce

severely or negate the "limiting levels" of ΔK below which crack propagation is nonexistent at constant ΔK.

Finally, uncertainty arises because the fracture mechanics model applies directly only to a monolithic, nonredundant, single-load path structure containing a preexisting defect (or crack) that may be critical for both ultimate load and fatigue failure. Empirical assumptions are necessary if an analysis is applied to a redundant, multiple-load path, "damage tolerant" structure with (or without) preexisting defects. It is on these complexities that considerable work is required, and the success of the work will be predicated on a more accurate determination of operating conditions.

Missing from present service-life characterization procedures is a comprehensive risk assessment, such as referenced above; usually, a "safe life" is established without a qualification regarding the risk of a failure earlier than that life. Therefore, in the context of a fixed scatter factor, the concept of "safe life" assumes that the probability of individual structural failures in the fleet sooner than the "safe life" is insignificant. Since about 1950, fleet experience has shown this assumption to be without merit, and statistical interpretation of some existing crack-monitoring records also illustrates the error of such an assumption (Whittaker and Besuner, 1969).

Based on recent studies of the statistical variability of considerable fatigue data on specimens and structural parts of various materials assembled by the aircraft industry, scatter factor of 4.0 for aluminum structural elements and structure might represent a "median value." This factor, if

applied to the fatigue life established in a full-scale test, would produce a "median safe life" associated with an even chance of not being attained or exceeded. For high-strength aircraft steels and titanium alloys, even this "median" scatter factor exceeds the value of 4.0 and varies roughly from about 4.5 for steels in the strength range of 100 to 200 ksi, to 6.0 for titanium alloys, and to in excess of 8.0 for ultra-high-strength steel in the strength range of 250 to 300 ksi. Unfortunately, the confidence limit of these factors (0.5) is too low for a meaningful reliability analysis. During the past 10 years, the U.S. Air Force has sponsored research to develop methodology for reliability analyses on airframe-structure fleets (Freudenthal, 1967; Whittaker and Besuner, 1969; Forney, 1972). Such a methodology would predict the time to the first failure in a fleet of any given size and for any given probability and level of confidence. Probability theory, based on averages and deviations from averages, has been applied to life-prediction analyses for some time. The introduction of the modern theory of order statistics and, in particular, extreme value statistics permitted relating (as a calculable number) the "time to first failure" to the "safe life" of a fleet (wherein the probability of exceeding this life in the fleet is defined as the fleet reliability). In such analysis, the risk of "premature" failure can be determined quantitatively within a statistical framework. During the last three years, validation of the potential of the proposed reliability-analysis methods have been sought by comparing life-reliability predictions and actual fleet performance of the USAF KC-135, C-130, C-141, and F-4 fleets with encouraging results.

A comparable risk-assessment methodology has not been developed for, or applied to, life predictions based on a fracture-mechanics model of subcritical crack growth to critical size.

On the contrary, the methods of fracture mechanics normally have been considered deterministic in nature, thereby not lending themselves to a risk assessment. Relatively little attention has been given to analytical development of the statistical character of the fracture process. Performing a meaningful risk assessment associated with life predictions within a reliability framework and within the state of the art of fracture-mechanics methods requires detailed knowledge of statistical properties of involved factors including:

(1) the statistical distribution of K_{Ic} ;

(2) the probability of variability in flaw growth (da/dN) due to the statistical character of spectrum loading;

(3) the probability associated with the detection of defects greater than some given size using the appropriate NDE method; and

(4) a comprehensive experimental measure of the scatter (shape factor) associated with the crack-propagation properties as a function of the material.

Although very little work has been reported on the problem of risk assessment involving crack propagation and the detection probabilities in terms of a reliability analysis, the subject is beginning to receive attention (Whittaker and Saunders, 1972). At present, a risk assessment in the proposed process of fracture-mechanics-based life prediction, and the definition of proper inspection intervals to assure integrity, can be done only in qualitative terms.

b. Required Research and Development

Concentrated effort should be devoted to the development of statistical characteristics of all factors involved in fracture-mechanics-based damage accumulation and life-prediction methods. Also, the type of reliability-risk analysis method described above should be extended to be applicable to the flaw-growth analysis concepts under current study. Any proposed reliability-risk analysis method should be capable of establishing:

(1) a time-to-first-failure prediction based on fleet size, flaw-occurrence probabilities, usage statistics, and scatter in da/dN;

(2) inspection intervals to find cracks prior to their growth to predetermined critical sizes; and

(3) the risks, associated with the above, that account for

   (a) statistical variability in the physical processes, and

   (b) the statistical aspects of the NDE processes (e.g., probability of overlooking existing cracks or flaws).

C. Implications of Incorporating Fracture Control

1. Design

The implications of incorporating a specific fracture-control requirement, such as that imposed on the B-1 program, and are not completely clear. The penalty in terms of weight and cost only can be assessed accurately by evaluating the detail designs that evolve.

This initial attempt may prove to be either insufficiently demanding or far too restrictive. In either case, the result of the B-1 program will not be known for many years but fracture control must be considered for new generations of vehicles before that evidence is in hand. At present, the best approach is to project the expected results if the various available design options are exercised.

If the safe-life structure concepts are used, only minor weight penalties may accrue since the major problem areas are associated with stress concentrations and the reduction of stress levels in those specific design areas. However, penalties will be incurred in cost and schedule due to the increased analysis and testing that must be performed. The crux of this situation is arriving at a testing level that is mutually agreeable to the manufacturer and customer and that will give the desired degree of confidence in the results at a cost acceptable to both.

There is a trend, particularly on the part of designers of large transport-type aircraft, to resort to fail-safe or crack-arresting design concepts. Although these concepts effectively may prevent catastrophic failures, they make the design more complex and generally add a weight and cost penalty.

When these concepts have been employed, in some instances higher strength material than normally specified for a monolithic-type design has been used to avoid weight penalties. Such changes increase testing needs to demonstrate fail-safe capability.

If the concept of preexisting cracks is accepted for all designs, much more extensive and frequent inspection intervals of the fail-safe structure could be required than analysis for a safe-life design could justify and would be the consequence of a faster allowable crack-growth rate. Another factor to consider in choosing a design concept is the consequence of the structural failure, such as the rupture of fuel tanks, that may not be catastrophic in nature, but that will reduce structural stiffness and possibly affect flying qualities or result in fracture, etc.

In any event, an obvious increase in cost is associated with the initial design process and results from using additional material, element, testing, required component testing, additional analysis, and detail design refinements.

Probably, an accurate assessment of the impact of incorporating fracture control can never be made. The problem is similar to the imposition of specific fatigue requirements in the last several years. When the fatigue requirements were established, it generally was believed that severe weight penalties would be incurred; however, today these penalties are negligible except when design refinement by more analysis is attempted. In general, it has been recognized that fatigue testing of representative components and the entire aircraft is necessary early in the development program.

2. Manufacture

The introduction of the fracture-control plan in manufacturing impacts principally on quality-assurance requirements. The postulation of defects occurring during the manufacturing process requires that the quality-assurance procedures will detect these within certain limits. For higher strength materials in their usual applications, the level of defect detection must be small if reasonable inspection intervals in service are to be attained.

Past experience has proven adequately that a variety of material defects can occur in all steps of the manufacturing process starting from the cast ingot. Aerospace-industry practice has been to perform multi-inspections after each of the manufacturing steps; however, the adequacy of these inspections to detect flaws or defects of important size has not been demonstrated unequivocally. Multi-sequential inspection does increase the probability of uncovering a defect that occurred early in the manufacturing process, although defects admittedly may pass through the inspection screen.

The inspection effort, required to assure overall higher quality, is a significant factor in manufacturing cost since it requires more complex and exotic equipment in addition to increased manufacturing manhours. In order to utilize these advanced inspection techniques effectively, it is necessary to use more knowledgeable personnel and implies more extensive training of quality-assurance personnel.

In addition to the problems of inspection during the manufacturing process, the people involved in the actual fabrication and manufacture must become aware of the significance of

relatively small defects or departures from design requirements. The principle that quality cannot be inspected into a part, must be emphasized, and pride in workmanship must be reinstilled into the production workers. The problem is confined not only to the mechanical manufacturing operations, such as machining, but also the various chemical operations that are necessary to perform these processes. The susceptibility to environment of some materials, particularly that of high-strength or refractory steels to chemical environment, has led to significant stress-corrosion problems in the past.

The ultimate measure of the possibility of incorporating fracture-prevention principles or a fracture-control plan in manufacturing is the cost involved, just as it is with design. While the information necessary to precisely judge the cost factor is not yet at hand, incorporating fracture-prevention principles appears to be expensive.

3. Operation

The impact of incorporating specific fracture-control procedures in the operation and maintenance of an aircraft may be related directly to the tolerance of the structure to defects, either service-induced or preexisting from the manufacturing process. The design concept may be a factor in the cost; for example, while fewer inspections may be required of a fail-safe design, the complexity and difficulty of the inspection could be increased in the process of gaining adequate residual structural strength after the first failure. A tolerant structure, i.e., one that will permit crack sizes large enough to be detected visually, is obviously most desirable and should be the objective for design. To achieve this objective in high-strength materials, plane-stress fracture conditions are necessary and

are not obtained easily in high-density structures without considerably improved materials.

The cost of obtaining, training, and retaining qualified personnel to accomplish the necessary inspections in the field will be even greater in the military than in industry. It is not possible to provide the necessary background knowledge for intelligent inspection of critical structures in a short time since this knowledge includes the manual techniques and some understanding of the environmental protection required during maintenance (particularly during reassembly of a component).

A fracture-control plan also may extend to the higher levels of the operational user's command. The rotation of an entire fleet through various activities may be desirable to balance the usage accumulated on individual airframes. For example, a plan might be implemented to insure that a single airframe would not stay in a gunnery training activity longer than a prescribed time period (in terms of flight hours) before being transferred to an operational squadron or some other activity with a different primary utilization.

A final operational impact should be mentioned since tentative moves in its direction are already evident in the Air Force. This impact is the possibility of maintaining usage records on aircraft on a tail-number basis and, in some of the grander propos schemes, on a major component, i.e., wing, horizontal and vertical tail, and fuselage. This activity would be extremely costly and should be examined closely to evaluate its economic merit.

D. Research and Development Required to Improve Fracture Control

At present, an emotional atmosphere surrounds aircraft structural problems. The concept that there shall be no structural failures inhibits the determination of a "good" fracture-prevention program. As a matter of historical fact, constraints always have been placed on the amount of money (whether translated into schedule, or quantity, or anything else) to be spent to acquire a particular operational capability. Techniques have grown up in a collection of analytical methods, termed "cost effectiveness studies," for formalizing these constraints and making judgments on the relative value of satisfying or violating them. A basic question, "How much is fracture control worth?" must be answered. Rational discussion on implementing fracture control will be possible only when the answer to this question can be measured monetarily.

The keystone to this situation is a definition of a statistically acceptable failure rate. One of the first research tasks in this area should be explicit determination, by aircraft type, of an acceptable structural failure rate. Clearly, such a determination is a distasteful undertaking but it is demanded if a consistent approach to fracture control is ever to be achieved.

A research effort should be started specifically to evaluate, on the basis of relative life-cycle costs, various alternatives to the idea of assuming a preexisting flaw in a new airframe component.

One possible effort could involve the summary disqualification of metals from the materials-selection population that

exhibit plane-strain fracture behavior in the thicknesses involved. Perhaps, other research programs could be developed if the use of linear-elastic fracture-mechanics concepts were not necessarily the dominant factor in the search.

Specific research and development tasks that are associated with each of the elements of a fracture-control plan were presented earlier in this section and the majority of these recommendations refer to ideas from the current state of knowledge of fracture mechanics discussed in the following section.

IV. FRACTURE TECHNOLOGY

A. Introduction

Approaches to structural-failure control of aircraft have evolved concurrently with developments in structural design and knowledge of service severity. Considerations of static strength and stability of components have been standard procedures for a long time. For approximately two decades, attention has been given to the fatigue life of "unflawed" structures. New or updated failure-control procedures have superseded existing ones and have prescribed progressively tighter constraints within which a reliable structure must be designed, manufactured, and operated.

Recent experiences with higher stresses, high strength materials, more severe environments, new fabrication methods, and structures subjected to longer service lives have focused attention on the sensitivity of these structures to small flaws that may not affect static strength. Fracture, emanating from these flaws, can occur within the useful lifetime of the structure. Thus, "fracture control" of flawed structures has evolved, concurrently with other failure-control approaches, to refine further the design, manufacture, inspection, and operation of aircraft structures.

The statistical aspects of service loads, material properties, and fatigue life suggest that further evolution of, or new approaches to, fracture control are needed. Many factors influencing fracture can be described more adequately in terms of a probability approach. Thus, existing deterministic approaches to fracture control are expected to be supplemented

and modified by probabilistic concepts, some of which may be employed today. Most probabilistic approaches, however, appear to require further development, and an adequate data base must be established before such approaches can be applied with confidence. With regard to many questions concerning materials selection, design stress levels, inspection, etc., deterministic approaches are of primary importance at present.

In this portion of the report, structural strength and life are considered within a deterministic framework that includes the design-load spectrum, a finite number of critical components, and/or a finite number of redundant members, only one of which may be fractured. Consequently, the stress analysis presumably may be refined to a high degree of accuracy. Finally, variability of material properties is considered in terms of a distribution function characterized by two or three parameters. Large flaws and cracks are assumed to be detectable and capable of characterization. The feasibility and accuracy of the inspection procedure are topics for discussion.

A certain finite number of components of a particular aircraft structure is critical to the structural integrity. These include parts of the wing (main box, spars, skin, stringers, fuselage attachments, swing wing pivot, actuator linkage, lugs, etc.), the stabilator and rudder, control surfaces, and possibly the landing gear. While additional items undoubtedly can be listed, these are typical examples of critical components. Many of these components are determinate or of low-order redundancy. Generally, rapid crack

extension that leads to the fracture of any one of these components could endanger the structural integrity of the aircraft.

The fracture-control plan should identify all critical locations within each of these members. Next, based on knowledge of the toughness of the <u>as-fabricated</u> component, a critical crack size and configuration, a stress-intensity factor for the critical crack, and the stress in the critical location must be estimated. The stress normally corresponds to the peak load in the load spectrum or is specified otherwise; however, due to fabrication and load history, residual stresses probably are present and may be important. In rapid fracture, the peak-tensile stress is important.

The adequacy of the determination of a critical crack size obviously depends upon the fracture toughness in the critical location, the accuracy of the overall stress analysis, the accuracy of the stress-intensity factor, and the good judgment exercised in assuming the critical location and crack shape.

The next step is the computation of an initial crack size from the critical crack size, the crack-propagation rate, and the stress histories. For aircraft load spectra, the actual stresses at the critical location, including mean and alternation stress history, are required. For a design load spectra that may be applied in relatively short repeated blocks, the cyclic history influence is introduced partially.

At the present state of technology, crack propagation is modeled by applying stress history to a specimen that matches the local stress history at the critical location in the

aircraft component. Crack-propagation rates, derived from such tests, are directly applicable to the computation of initial crack size in a component.

Computations of initial crack size (at beginning of life) lead to one of two possible conclusions: either the initial crack size is sufficiently large to be found by inspection or the initial crack size is so small as to make detection uncertain or unlikely. If the first, obviously desirable, condition exists, inspection at the beginning of life has the capability to detect serious cracks that would lead to fracture within the design life of the component. If the second condition governs, detailed inspection will be necessary at this critical location at prescribed intervals during the life of the component. The crack-propagation rate now can be used to set suitable inspection periods for usage corresponding to the design-load spectrum. In both of the above cases, service environment must be considered. Obviously, whenever possible the crack-propagation rate data should be obtained in an environment typical of service.

Consideration also must be given to introducing these elements of fracture control into the complex process of design, fabrication, and testing of an aircraft structure, and this aspect of the subject is treated in Section III of this report. The remainder of this section of the report presents a review of the principal elements of fracture technology: fracture toughness, fatigue and subcritical-crack extension, metal improvement, nondestructive evaluation, and requirements for advancement of basic technology.

B. Fracture Toughness

1. Discussion

More efficient structures, based on a strength-to-weight ratio, have been evolved by using materials with higher yield and ultimate strengths. Stresses at design-limit loads have increased correspondingly. Fatigue strength for steel and titanium alloys frequently has been related to some fraction of the ultimate strength while for aluminum alloys, fatigue strength has remained relatively unresponsive to increases in static strength. With higher strength alloys, the influence of the environment in terms of corrosion and stress corrosion has increased the problems.

It is an axiom that the ductility measured in the standard tensile test decreases as the yield strength increases. Considering fabrication, the ductility necessary for past conventional forming has not been quantified. New fabrication techniques that are applied to low-ductility materials have reduced dependence on simple ductility tests and industry has learned to live with materials of reduced ductility.

The use of higher strength alloys for aircraft structures has increased and requires better quality control during fabrication, heat treating, finishing, and assembling. However, quality has not kept pace with the sensitivity of the components to small deviations from processing specifications and flaws. Fabrication and manufacturing methods can introduce small flaws and cracks that may be undetected by their practices or limited by present NDE technology. The high-strength materials frequently are very sensitive to small variations in heat treating; they are in a ductility or

toughness range of little "forgiveness." In service, the components are sensitive to overstressing due to slight miscalculations in design and stress analysis, and small service-induced fatigue cracks develop. Flaws and cracks, whether induced during manufacture or service, become critical at surprisingly small sizes, particularly when coupled with an unfortunate variation in quality control (i.e., during heat treatment) and an aggressive service environment. The obvious answer is to introduce "quantitative fracture-toughness requirements;" however, fracture-toughness technology is incomplete at this time and is not a simple, quick, inexpensive, easy-to-apply remedy for all problems.

Two extremes exist. Fracture-mechanics technology can be relegated to a minor position and be used after all major decisions are made to satisfy contractual requirements; "fixes" will be applied to any deficiencies that are uncovered. Conversely, linear-elastic fracture mechanics can be used (or abused) to make all decisions, even when very conservative, expensive decisions result from an abuse of the technology. Both extremes represent poor engineering and management; neither can be tolerated for a satisfactory cost-effective structure.

A "fracture-control plan" is essential to avoid these "extreme" uses of fracture mechanics and to arrive at a rational, reasonable application of fracture-mechanics technology to insure adequate toughness. The primary objective must be to design and build, at a minimum cost and in a reasonable time, a reliable aircraft structure that meets performance requirements.

With this objective in mind, an examination of the present fracture-mechanics technology and some of the problems that arise is in order.

Fracture toughness applies to crack-like flaws (such as the last cycle of fatigue) regardless of how the crack originated. The important parameters are the crack size, local stress in the absence of the crack, yield strength, and fracture toughness. A brief introduction to fracture-mechanics technology is contained in Appendixes B and C.

An illustration will clarify appropriate uses and common abuses of current plane-strain fracture toughness, K_{Ic}, technology. Testing to measure K_{Ic} has been standardized by the American Society for Testing and Materials (ASTM); accordingly, it is tempting to employ K_{Ic} testing and results for many purposes where toughness is a requirement.

Consider three steel components each loaded in axial tension with a yield strength requirement from 220 to 240 ksi. Current high-quality steels may exhibit a mean fracture toughness of 110 ksi $\sqrt{in}$ corresponding to the lower limit of the yield-strength range and 80 ksi $\sqrt{in}$ at the upper limit. One of the components is sized, based on standard static strength and fatigue analysis, to have a cross section 1-inch thick and 6-inches wide. A second component is a wide, flat plate 0.25 inch thick. The third component is a wide sheet 0.060 inch thick. Certainly, changes in cross section, holes, and cutouts are regions of stress concentration and may be the critical regions of highest stress. However, for this illustration, no generality is lost if a semi-elliptical surface crack, located in a plate or sheet member normal to the uniform tensile-stress field, is employed.

For illustration, two questions are asked:

a) What is the critical flaw size that will cause rapid fracture if each of these components experiences a peak tensile stress of $\sigma = 0.8\,\sigma_{ys}$?

b) Is plane strain fracture toughness, an appropriate means to specify toughness of the material in each of these components?

The computations of the critical flaw sizes for semi-elliptical surface cracks are shown in Appendix A. The results in Appendix A list critical crack sizes for both the lower yield strength, σ_{ys} = 220 ksi (K_{Ic} = 110 ksi $\sqrt{in}$) and the upper yield strength, σ_{ys} = 240 ksi (K_{Ic} = 80 ksi $\sqrt{in}$) for four crack shapes. Selecting a crack shape, a/2c = 0.33, typical of many fatigue cracks, the critical crack depth, a, ranges from 0.169 inch for the lower yield strength to 0.079 inch for the upper yield strength.

Compared with the component size, these crack dimensions appear reasonable for the 1-inch-thick steel component. However, this entire range of crack depths penetrates completely through the 0.060-inch-thick sheet, and the analysis must be revised to reflect a through-the-thickness crack, a modification that can be made easily.

The major problem illustrated by this example is that the K_{Ic} fracture toughness is not appropriate to represent the toughness of the 0.060-inch-thick sheet, and it is marginal for the 0.250-inch plate (see Appendix A). To develop the minimum toughness (independent of thickness) represented by K_{Ic}, full constraint (triaxial stresses) around the crack

border must be present. As specified at the end of Appendix A, both specimen and component thickness must exceed 0.620 inch for the lower yield strength, σ_{ys} = 220 ksi, and for the upper yield strength level 0.280 inch.

For the component 1 inch thick and 6 inches wide, a suitable K_{Ic} specimen can be obtained from a 1-inch-thick plate, and a valid test may be expected over the entire range of acceptable yield strengths and toughnesses. For this component, a K_{Ic} specification for material is appropriate and useful. Note that the critical crack size is relatively small, and nondestructive testing must detect initial cracks that are considerably smaller than the critical size.

Valid K_{Ic} specimens of sufficient thickness cannot be cut from the 0.250-inch plate even for the upper level of yield strength. For material with all combinations of yield and toughness within the acceptable material limits, 0.25-inch-thick specimens would give values of toughness that were not valid K_{Ic} numbers because the specimen thickness is too small to develop sufficient triaxial constraint to obtain K_{Ic}. If K_{Ic} material specifications are required, a thicker plate must be used to obtain a valid K_{Ic} measurement. One could purchase thicker plate, make the K_{Ic} test, and then machine the plate to desired thickness for the component. This would meet specifications. Conversely, one could attempt to lower the specification on toughness to a point where all 0.25-inch-thick plate, heat treated to a lower toughness, would provide a valid test. Again, this would satisfy the letter of the specifications. However, both of these approaches represent utter nonsense.

In the first case, cost and time are increased with no benefits. In the second case, toughness and, consequently, reliability are sacrificed. Clearly, a K_{Ic} specification is useful for the 1-inch-thick plate and abused and detrimental for the 0.250-inch-thick plate.

In order to avoid any misunderstanding, fracture toughness of a service component is a function of both material and geometry (in this case, thickness B) of the component. Any toughness specification that does not quantitatively account for material, geometry, and stress level is not utilizing fully the toughness potential of the metal or the existing technology.

For the 1-inch-thick and 6-inch-wide component, K_{Ic} is useful and appropriate because K_{Ic} will govern fracture of this component in service.

For the 0.250-inch-thick plate, K_{Ic} will be below the minimum toughness that will represent the service component. Even for the maximum yield strength specification, relaxation of triaxial constraint may elevate the toughness of the service component above K_{Ic}. This increased increment of toughness should be used. The obvious way to treat this situation today is to model the expected crack in a laboratory specimen using the same thickness for the model as the service component. Fracture mechanics provides useful guidance for planning and performing the model test.

The present problem is that a standard test is unavailable for this condition and cannot be specified in material specifications. The needed standard test for thin materials could be developed, however, if adequate financial support were available.

The sheet material, 0.060 inch thick, will not allow preparing an adequate specimen for determination of K_{Ic} and its behavior will not be governed in service by the K_{Ic} toughness. Undoubtedly, a K_{Ic} specification is completely inappropriate in this situation. Again, Appendix B discusses several helpful methods for modeling the service crack in a laboratory specimen in order to measure, judge, and control toughness. As yet, there are no standard tests for thin sheet applications and, unfortunately, each situation must be considered individually.

Fracture-mechanics technology provides adequate tools for modeling service cracks for determining the structural reliability of the fleet of vehicles, but the technology does not provide a simple property and standard test method that may be quoted in material specifications.

Potentially of great importance is the influence of thickness on the measured toughness and critical flaw size. The sheet material, 0.060 inch thick, was used in this example to emphasize the fact that the toughness is increased when the thickness and constraint are reduced. There is an optimum thickness where the toughness measured by K_c or an R curve is a maximum. This maximum toughness may be at least 1.5 to 3 times higher than the toughness of thicker components of the same material (same heat treatment, yield strength, etc.). This increase in toughness results from the relaxation of transverse triaxial constraint quite independent of the strength and metallurgical condition of the material.*

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* Usually, the additional working given thin sheets further enhances the toughness of the thin sheet as compared with thicker plate.

In terms of critical flaw size, this corresponds to a factor of from 2.2 ($K_c = 1.5\ K_{Ic}$) to 9 ($K_c = 3\ K_{Ic}$) over the flaw size for a thick member (K_{Ic}). This larger final flaw size may increase the reliability of inspection of service components from a marginal situation to one of high reliability.

2. Conclusions and Recommendations

a. Conclusions

(1) Using an illustration, this section has indicated that fracture toughness, K_{Ic}, is useful and appropriate for materials specifications and for a guide to needed NDE sensitivity by specifying the critical crack size for members of sufficient size.

(a) For thin plates and sheet materials, a K_{Ic} specification frequency is inappropriate and, when improperly used, encourages incorrect actions in an attempt to meet such a specification.

(b) When the size requirements for K_{Ic} are not met in both the specimen and the service component, fracture mechanics offers guidance in laboratory modeling of cracks to simulate service behavior. This approach can provide the same reliability and confidence that is achieved by using the K_{Ic} toughness. However, a standard test and property that can be quoted in specifications are lacking.

(2) Standardization efforts for toughness have been underway for more than 10 years. However, the problem is complicated, and financial support for this work always has been meager. Several recent theoretical advances appear very promising, and suitable standard properties and tests could be developed within several years if this work would be supported adequately.

(3) At this time, metals producers are uncertain of the process and metallurgical requirements to control toughness. Research and development work are needed to ascertain the process and physical metallurgy variables that influence toughness (see Section IV-D).

(4) To advance the technology so that fracture-toughness specifications can be nearly complete and adequate, the toughness property, the standard test for it, and the means of controlling toughness must be established.

(5) In the past, much of the work in this area has been supported by metals producers and NASA. Short-term efforts of the Department of Defense related to, and controlled by, hardware projects also have provided support but such efforts are unsatisfactory in terms of continuity and progress.

b. Recommendation

Support is recommended to develop standard fracture-toughness characterization properties for thin plate and sheet materials and to standardize test methods to measure these properties.

C. Subcritical Crack Growth: Fatigue and Stress-Corrosion Cracking

1. Significance of Subcritical Cracks

Defects in modern, high-performance structures can produce a fracture either immediately, the first time the structure is fully loaded, or after an elapsed time in service.

The "immediate" failure is caused by a pre-existing crack that is larger than the critical size.* The "delayed" failure is caused by a "subcritical" crack--a pre-existing crack smaller than the critical size.

The idea that subcritical cracks are dangerous may seem a contradiction of fracture mechanics in which they are defined as stable and benign. However, this concept is based on the idea that the material at the crack tip does not deteriorate with time, an assumption that frequently is invalid. There are, in fact, three very common situations that lead to deterioration:

a. fatigue -- cyclic loading;

b. stress-corrosion cracking** -- sustained loading in the presence of a corrosive environment; and

c. fatigue in the presence of a corrosive medium -- combinations of a and b above.

The progressive deterioration of the material at the crack tip causes a subcritical crack to grow slowly in a stable fashion. Slow growth continues until the crack attains the critical size determined by the fracture toughness, when

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* The critical crack size, a*, is determined by K_{Ic}, the fracture toughness of the material, and σ, the applied stress: $a^* = \frac{AK_{Ic}^2}{\pi\sigma^2}$, where A is a geometric factor of order unity. These concepts and the problems of characterizing K_{Ic} are discussed in Section IV-B and Appendix B.

** In some cases, stress-corrosion cracking may be related to the dissolution of hydrogen at the crack tip followed by hydrogen embrittlement. Pre-existing, dissolved hydrogen and possibly other interstitials may contribute to the deterioration of the material at the crack tip and cause crack growth.

rapid, unstable fracturing intervenes (Fig. 1). Tables 1 and 2 and Figure 2 are examples of the effects of stress-corrosion cracking and fatigue on the time-to-failure for two high-strength alloy plates containing a subcritical crack. More complete discussions of fatigue and stress-corrosion cracking appear in Appendix C, "Subcritical Crack Extension."

Subcritical cracks that attain critical size during service life are, therefore, just as dangerous as the preexisting critical defect In some respects, they represent an even greater problem to the designer for the following reasons:

a. Subcritical defects are, by definition, smaller, more difficult to find, and more likely to escape detection than critical defects.

b. Subcritical crack growth can occur in many materials under a variety of service conditions.

c. Subcritical crack growth tends to be most rapid in high-strength alloys that possess low toughness levels; therefore, growth to critical size is most likely in alloys that present the greatest inspection problems.

d. The control plan for subcritical cracks hinges on accurate predictions of crack growth. Since the growth rate is sensitive to loading history and environment, the predictions require accurate forecasts of service conditions and their simulation in the laboratory.

2. Subcritical Crack Growth

During the past decade, research on subcritical crack growth has established that the growth rate, $\left(\frac{da}{dt}\right)$, the growth velocity under sustained loading, and the per cycle growth increment in fatigue, $\left(\frac{da}{dn}\right)$, correlate with the fracture-mechanics parameter, (K), that describes the stress-field

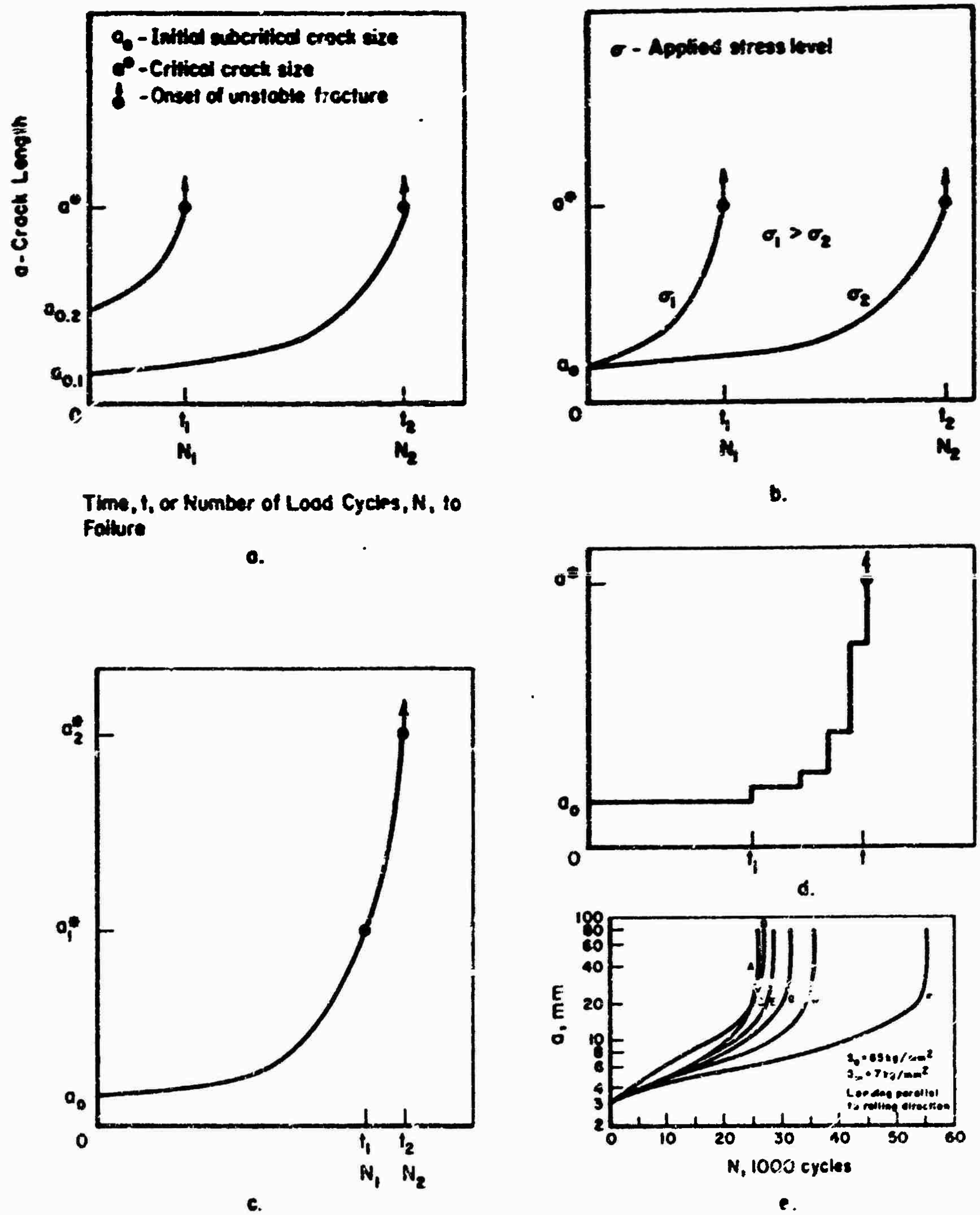

FIGURE 1. Examples of Subcritical Crack Growth. Figures (a), (b), and (c) are schematic representations showing the influence of the initial flaw size, a_o, the applied stress level σ, and the critical flaw size a* on the number of load cycles N or time t to failure under cyclic or sustained loading. Figure (d) illustrates the incubation time t_i and discontinuous growth displayed by stress corrosion crack growth in some materials. Figure (e) reproduces actual fatigue crack growth curves for several heats of 2024-T3 Aluminum.

Source: Hartman and Schijve, 1970.

TABLE 1. Influence of Various Crack Environments on Failure Time of 300 M Steel*.

Environment	Failure Time (min)
Recording ink	0.5
Distilled water	6.5
Amyl alcohol	35.8
Butyl alcohol	28.0
Butyl acetate	18.0
Acetone	120.0
Lubricating oil	150.0
Carbon tetrachloride	No failure in 1280
Benzene	2247.0
Air	No failure in 6000

* 300 M Steel with a yield strength of 245 ksi under a net section stress of 75 ksi; initial sub-critical crack size, 0.375 inch.

Source: Steigerwald, E.A., 1960.

TABLE 2. Variables Affecting Fatigue and Stress Corrosion Crack Growth Rates.

1.	Crack length
2.	Applied stress or stress range* K or ΔK
3.	Crack-component geometry
4.	Applied stress- or cyclic-stress* environmental history
5.	Stress ratio*
6.	Cyclic frequency*
7.	Temperature
8.	Alloy composition
9.	Heat treatment and processing history
10.	Hydrogen content and other trace impurities
11.	Composition of chemical environment
12.	Plate thickness (plane stress versus plane strain)
13.	Fracture toughness

*Variables peculiar to cyclic crack growth.

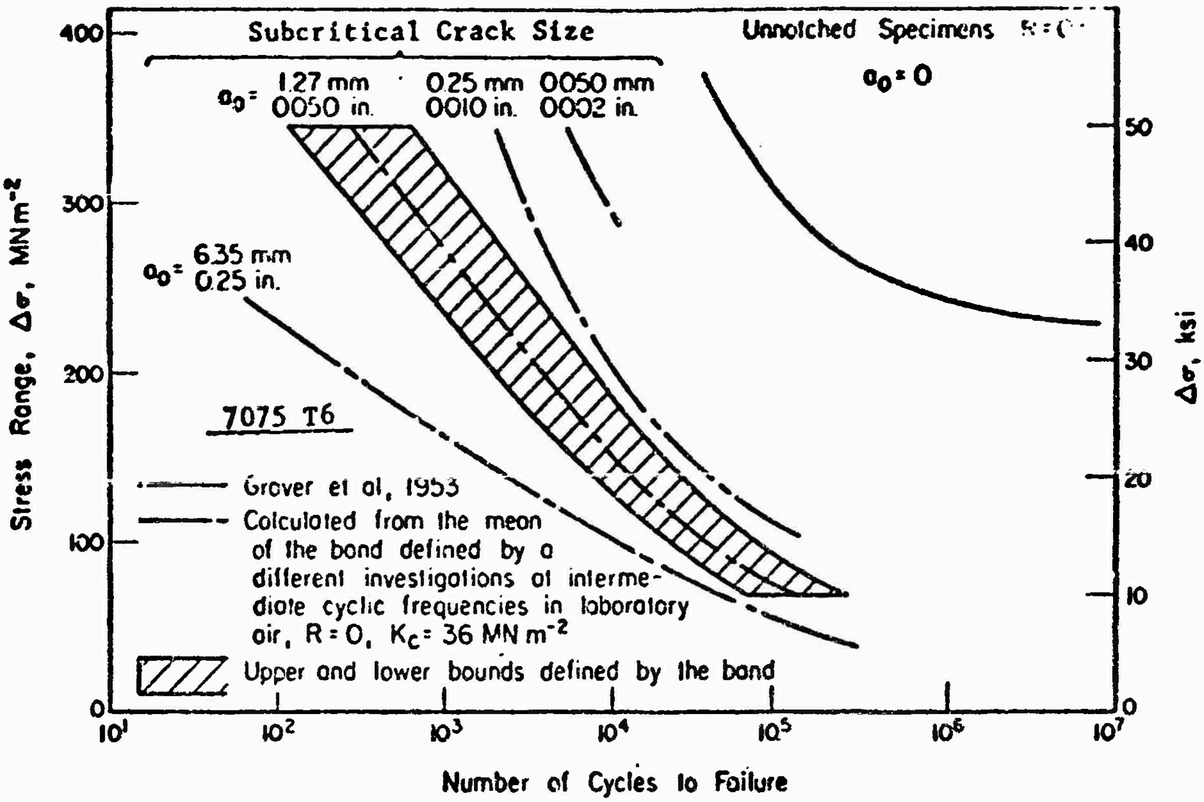

FIGURE 2. Influence of Subcritical Crack Size and Cyclic Stress Amplitude on the Life of 7075-T6 Panels with a Centrally Located Defect.

Source: Hahn and Simon, 1972.

intensity of the crack. Examples of growth rate, K, dependence are given in Figure 3. These have several implications:

a. Larger cracks tend to grow faster than smaller cracks because they produce larger K-values (see Fig. 1a). Cracks also tend to grow more rapidly at higher stress levels for the same reason (see Fig. 1b).

b. Crack growth accelerates as the crack grows: (1) because K-values increase with crack length (see Figs. 1a and 1b); and (2) because the growth rate is a rapidly varying function of K (Fig. 3a).

c. Because of the acceleration of crack growth with time, increases in a*, the critical flaw size, do not produce corresponding increases in the life of the component (see Fig. 1c). Further improvements in service life can be obtained by reducing the initial flaw size (improvements in material quality and NDE procedures) and by reducing the growth rate (see Fig. 1e).

d. The growth rate decreases rapidly below a certain K-level (see Figs. 3a and 3b). This has been interpreted as evidence that both fatigue and stress-corrosion cracking involve a Threshold-K, similar to the endurance limit, below which cracks do not grow. The Threshold-K for stress-corrosion cracking is called K_{Iscc}.

An integration of the growth rate-K dependence* (the functional relations illustrated in Figure 3b offer an estimate of the time or number of cycles to failure. However, such estimates involve a number of complications:

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* For example, for cyclic crack growth $\frac{da}{dN} = f(\Delta K)$ and $N = \int_{a}^{a^*} f^{-1}(\Delta K)da$. This integration can be performed if the ΔK-crack length dependence and the values of a_o and and a* can be defined.

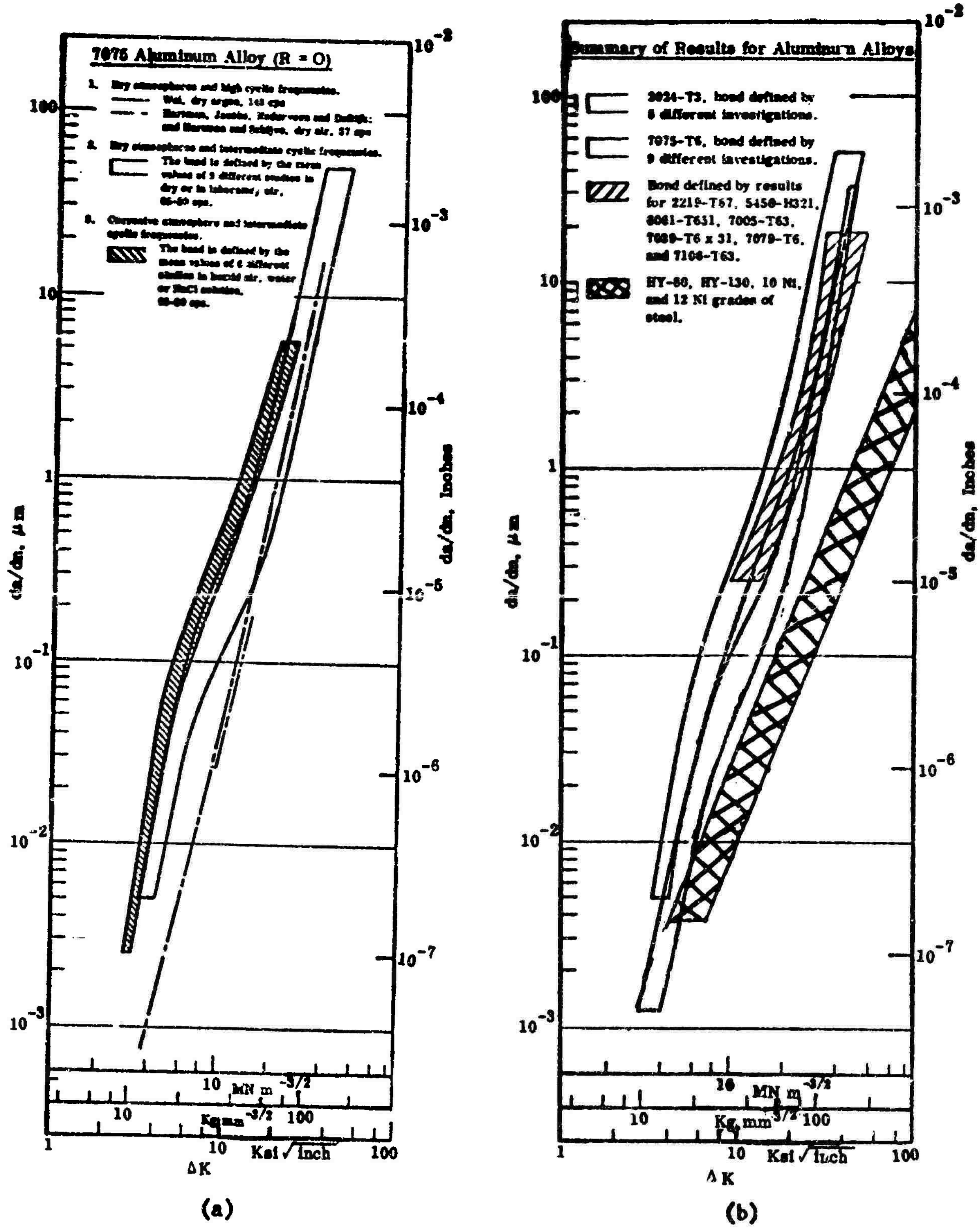

FIGURE 3. Summary of Cyclic Crack-Growth Measurements: (a) influence of environment and cyclic frequency on cyclic growth in 7075-T6 and (b) results for different aluminum alloys and steels.

Source: Hahn and Simon, 1972; Barsom, 1971.

a. Environment. Figure 3a illustrates that the cyclic crack-growth rate is sensitive to the composition of the environment (in this case, the humidity). The same is true for stress-corrosion crack growth. Consequently, failure-time calculations are meaningful only to the extent that the service environment is reproduced faithfully in the laboratory. Under fatigue loading, the cyclic frequency also becomes an important variable when environmental effects are involved.

b. Loading History. Growth-rate measurements, performed at constant or gradually varying cyclic stress amplitude, do not reproduce growth under conditions where large variations in amplitude are encountered. This problem can be handled by reproducing the service "load spectrum" in the laboratory. However, a way of synthesizing the effect of a spectrum from constant amplitude data is needed to reduce the burden of testing. Effects of prior history and periodic unloading also may be encountered in stress-corrosion cracking.

c. The Incubation Time and K_{Iscc}. In some materials, stress-corrosion crack growth involves an incubation period (t_i in Fig. 1d). At low K-levels, finite growth rates then are observed only after a long incubation period, and this can be confused with the penetration of Threshold K_{Iscc} if the test is stopped prematurely. This incubation period (discussed more fully in Appendix C) complicates the task of predicting growth and requires further study.

d. Threshold-ΔK. Under cyclic loading, the Threshold-ΔK may be related to the phenomenon of crack closure, the development of residual stresses that press the faces of the crack together. This phenomenon, which could affect

growth-rate predictions, is poorly understood and requires further study.

3. Fracture Controls for Subcritical Cracks

As a result of the research conducted during the past decade, much of it supported by the Department of Defense, considerable progress has been made in controlling failures originating from subcritical cracks. Methods of reproducing and measuring crack growth in the laboratory have been developed, although they need refining and standardization. Many important (but possibly not all) variables have been identified, and considerable data have been accumulated (see Appendix C for a more complete review). In principle, it is now possible to make deterministic predictions of the "safe life" or the "safe inspection interval" of structural components provided the initial flaw size, service-stress history, and environmental history of the component are defined and provided the growth rates corresponding to these very same conditions have been measured in the laboratory. Also, components can be designed (stress level and the choice of a material can be altered) to give a predetermined service life. While the sharp edge of these predictions is blurred by the specimen-to-specimen scatter encountered in testing, the dispersion appears to be no greater than that associated with the unnotched fatigue life of flaw-free specimens. Further uncertainties are introduced by the subcritical crack size that may be handled best in probabilistic terms. As proof of the viability of this approach, a fracture-control plan for subcritical cracks currently is being employed in the design of "fracture critical" components of the B-1 aircraft.

These developments have been facilitated greatly by fracture mechanics that permits representing crack length, stress level, and crack-component geometry by a single variable, K. However, the biggest problem encountered in the field of crack growth is the large number of additional variables that influence this growth rate. Some of these variables are listed in Table 2. Since the present understanding of the mechanisms of crack growth is largely incomplete, the effects of these variables, singly and in combination, must be determined by time-consuming and expensive laboratory measurements.

The long list of variables means that service history must be specified in great detail. It also means that laboratory simulations must be very specialized--virtually every component must be simulated--or large numbers of variables must be investigated for each alloy. In either case, testing is a great burden and, for some applications, prohibitive. More research is needed to develop analyses of the crack-growth mechanisms that will permit the more efficient deduction of growth rates with fewer measurements. In the meantime, service performance should be correlated better with standardized laboratory tests to obtain a meaningful data base for designers.

4. Recommendations

a. The designs of cracked specimens should be standardized for cyclic and stress-corrosion crack-growth testing.

This need for standardization has been recognized by the members of the ASTM Committee E-24 on Fracture Testing of Metallic Materials and by ASTM Committee G-1 on Corrosion, Deterioration, and Degradation of Materials. These committees have established a joint task group to draft standards or recommended practices for stress-corrosion tests using cracked specimens. Because the kinetics of the process are complex and as yet not completely understood, standards development will be an evolutionary process. At present, general agreement is needed on one or two specimen designs and the necessary operational controls for conducting the tests. In the case of cyclic crack growth, standardized test specimens, frequencies, environments, and load spectra must be established. These efforts require the participation of many individuals and laboratories and are hampered greatly by the lack of funds for experimentation and to meet travel expenses.

b. The mechanisms of cyclic crack growth, particularly corrosion fatigue, should be studied further to reduce the reliance on empirical testing.

In the case of fatigue-crack growth, efforts should be made to understand the elastic-plastic stress-strain distribution in the vicinity of the crack tip, the contribution of the cyclic flow properties that underlie crack closure, and spectrum loading effects. In the case of corrosion cracking, a better understanding should be obtained of the chemistry of the corrosion process as influenced by such factors as passivation of the crack faces, tightness of the crack, and application of protective measures. Without a better understanding of the available chemistry, it will be difficult to relate laboratory data to service applications.

c. The material, chemical, and geometrical factors that control incubation and growth in the vicinity of K_{Iscc} should be investigated.

Recent work has indicated that extremely long incubation times ($\sim 10^4$ min) often are required to initiate slow crack growth in the vicinity of K_{Iscc}. The reason for this effect and its implications for fracture control need to be defined. The relations between incubation and growth at low K-levels and corrosion fatigue should be examined with the aim of developing correlations between these processes. In addition, an understanding of the geometric and material effects that produce the extended incubation time may lead to the development of materials with improved stress-corrosion resistance.

d. Correlation of minimal laboratory test (or simulated service) data to actual component performance should be developed in the area of spectrum loading.

e. Regression parameters should be established for stress corrosion and cyclic crack-growth measurements in different materials.

A current round robin of collecting regression parameters for cyclic crack-growth measurements has been organized by ASTM-E-24 and is a useful first step.

D. Metal Improvement

1. Fracture Properties

a. Discussion

The primary goal for improving the fracture properties of metals is to increase the fracture resistance for a given strength level and section size. In addition to increasing the fracture toughness of a metal, it is even more advantageous to cause a change in fracture state for the thickness of the material under consideration. For example, a change in fracture state from plane strain to elastic-plastic, or a change from elastic-plastic to plastic, is more beneficial than an increase in toughness within a given fracture state. To obtain the desired increases in fracture resistance, the cleanliness of the metal must be controlled at the ingot stage. A detailed discussion on metal improvement is presented in Appendix E.

Table 3 presents a simplified rank-level characterization of metal properties in terms of two levels for each of the three possible fracture states. The table relates fracture state, fracture mode, and test-specimen criteria. The structural design significance is referenced to the fracture-extension stress for a through-thickness crack, which has a length of approximately two to three times the thickness. For the plane-strain state (valid K_{Ic} measurement), an increase in the K_{Ic}/σ_{ys} ratio results in an increase in the critical surface crack size for a specific stress level; however, for a through-thickness crack, the fracture extension stress usually is less than $0.30\sigma_{ys}$, which is less than the limit-stress level normally used for aircraft design. The elastic-plastic fracture state is more beneficial than the plane-strain state, as indicated by the

TABLE 3. Rank-Level Relationships.

Rank Level	Fracture State	Fracture Mode	Test-Specimen Characterization Criteria	Structural Design Significance
				(Fracture Extension Stress)
(6)	High Plastic	Full Slant	CR-E*	$>> \sigma_{ys}$
(5)	Low Plastic	Mixed Mode	CR-E (COD/J_c)	$> \sigma_{ys}$
			Yield Criterion	
(4)	High Elastic-Plastic	Mixed Mode	CR-E $(K_c/COD/J_c)$**	0.5 to 1.0 σ_{ys}
(3)	Low Elastic-Plastic	Shear Lips	CR-E $(K_c/COD/J_c)$	0.3 to 0.5 σ_{ys}
			Plane-Strain Limit Criterion	
(2)	High Plane-Strain	Flat	$\frac{K_{Ic}}{\sigma_{ys}} = 0.6$ to 2	$< 0.3\ \sigma_{ys}$
(1)	Low Plane-Strain	Flat	$\frac{K_{Ic}}{\sigma_{ys}} = 0.1$ to 0.6	$< 0.3\ \sigma_{ys}$

* Constraint Relaxation Index -- based on fracture energy or equivalent.

** See Appendix E.

Source: Naval Research Laboratory.

rise in the fracture-extension stress for through-thickness cracks. The plastic fracture state is the most desirable since gross stress levels greater than the yield stress are required for fracture.

The changes in fracture state, as well as the relationship between K_{Ic} (or Dynamic Tear (DT) energy) and the yield strength, are shown graphically by using the Ratio Analysis Diagram (RAD). (In Appendix E, Ratio Analysis Diagrams are shown for steel in Figures 27 through 35, for titanium in Figure 36, and for aluminum in Figure 37.) It is evident from the RAD that an increase in yield strength is coupled generally with a decrease in fracture toughness.

The objective in metal improvement is to increase the toughness without decreasing the yield strength. This can be accomplished by controlling the melting process so that the resulting metal is of very high purity. High cleanliness reduces the number of nonmetallic particles that promote early void initiation during the process of crack-tip plastic zone growth.

There are three quality groupings for steels with regard to cleanliness: (1) conventional air-melting steel that has relatively high phosphide, sulfide, and aluminum oxide phases; (2) special slag plus vacuum-arc remelting that has lower P and S levels in addition to lower oxygen content; and (3) vacuum-induction melting plus vacuum-arc remelting steel that is of very high purity. The effect of cleanliness in steel is reflected in the three quality corridors shown in the ratio analysis diagrams (see Figs. 30-32, Appendix E).

Oxygen content is the primary metal-quality factor in titanium alloys. Higher oxygen content promotes increased yield strength but causes a reduction in fracture toughness. Two metal-quality corridors are shown in Figure 36, Appendix E.

In aluminum alloys, large amounts of brittle intermetallic compounds are present and serve as initiation sites for microcracking and void initiation. Research aimed at producing relatively clean metal should result in marked material improvements. Until recently, only one quality corridor existed for aluminum, but new experimental alloys with higher toughness fall above that corridor on the RAD (See Fig. 37, Appendix E).

Appendix E contains a complete list of conclusions for metal improvement for increasing fracture resistance; a summary of those conclusions is given in the following paragraphs.

b. Conclusions

(1) For a given section thickness, increasing strength generally causes a decrease in fracture resistance, from plastic to elastic-plastic and then to plane-strain states. This effect is defined as the "strength transition," i.e., a strength-induced transition.

(2) Improvements that elevate a metal from plane-strain fracture to elastic-plastic fracture are highly significant because they imply large increases in critical crack sizes for regions of high as well as low relative stress.

(3) If a minimum level of fracture properties (K_{Ic} or elastic-plastic) is specified, an upper yield-strength limitation must be accepted. Conversely, if a minimum yield strength is specified, then a fracture-toughness limitation must be accepted.

(4) All metals feature an intrinsic "quality" for resisting the incubation and growth of microvoids as the grain structure is subjected to plastic flow at crack tips. The quality aspect is cleanliness, i.e., the relative concentration of nonmetallic phases "foreign" to the metal-grain structure. A reduction in the number of sites that promote microseparations of the metal grains results in increased fracture resistance.

(5) The cleanliness quality is decided at the time of ingot solidification. Forging or heat-treating effects can influence fracture properties, for a specified strength, only to ceiling levels dictated by metal-quality factors.

(6) Steels feature three quality corridors of strength-induced transitions corresponding to (a) relatively poor, (b) intermediate, and (c) high levels of cleanliness. The levels of cleanliness result from the melting and subsequent processing procedures. The highest corridor represents premium-quality metal. There are relatively limited expectations for additional improvements of major scope, i.e., to a higher (fourth) corridor.

(7) Reasonably extensive investigations have been made for titanium alloys. Two metal-quality corridors have been identified. There are reasonable expectations that a third (higher) corridor quality may evolve by controlling processing factors. However, these premium-quality materials (the second-corridor level, featuring low-oxygen contents) should be used.

(8) The metal-quality factors of aluminum alloys have not been investigated adequately. Prior to 1970, the aluminum alloys were limited to one low-quality corridor.

Recent experimental work on aluminum alloys has resulted in the start of an intermediate-quality corridor. Studies similar to those for steels are expected to evolve more metals of intermediate quality and, eventually, some metals with high-quality corridor features.

c. Recommendations

(1) The assessments for metal improvement expectancy given in Conclusions (6), (7), and (8) serve as recommendations that priority of further research effort be placed: first, on titanium because of its critical importance to advanced aircraft; second, on aluminum alloys because of their neglected state; and third, on steels because of their advanced technological status.

(2) For welded structure, all three metal systems should be investigated with equal emphasis.

2. Fatigue and Subcritical Flaw Growth

a. Discussion

In comparison to the resources that have been spent in improving the fast fracture properties of high-strength metals, the development of improved alloys to resist fatigue and other forms of subcritical flaw growth has received limited attention. The mechanisms involving slow crack growth are fatigue crack propagation, stress-corrosion cracking, and sustained-load cracking. Among these failure mechanisms, fatigue and stress corrosion have been the most widespread phenomena in aircraft structures. Stress-corrosion cracking is a phenomenon that is preventable generally through metallurgical control, alloy selection, and surface treatment to provide residual compressive stresses or protection from

corrosive environments. Sustained-load cracking (no corrosive environment necessary for cracking to occur) is little understood at this point, either as to its origins or extent. However, recent exploratory studies indicate that it is a serious threat to the structural integrity of some titanium alloys.

Fatigue is a multifaceted problem that has long been recognized by aircraft designers. The use of complex high-strength weldments in aircraft structures has raised the specter of fatigue failure by aspects of the problem not previously considered. Complex weldments are likely to involve regions of high stress concentration, plus a significant probability of defects occuring in the welds. The use of high-strength alloys implies high stress levels in such components. These factors combine to create a possibility of rapid fatigue crack initiation under service loads. Further, such components are likely to be located at positions within the aircraft where periodic inspection and repair of cracks are most difficult.

Thus, a refined knowledge of fatigue-crack propagation is necessary to guide the design of such components. Without such knowledge, the designer faces a dilemma between impossible demands for flaw-free fabrication and inspection and the unacceptable alternative of reduced aircraft performance and reliability.

Efforts at controlling this problem are only at an early stage of development. There is a brief discussion of metal improvements for cyclic crack growth resistance in Appendix E. Few serious attempts have been made to deal with the problem metallurgically, except through increased fracture toughness.

Alloys that possess high fracture toughness "tend" to have superior fatigue crack-propagation resistance when compared to their low-toughness counterparts. Most importantly, the use of of high-toughness alloys permits larger flaw sizes to evolve in service, thus extending fatigue life to some degree. However, the newest high-strength, high-toughness alloys have a certain aura of expectation about their performance that may lure designers into utilizing high design stresses with unjustified confidence. Under such conditions, any available marginal fatigue benefits can be overwhelmed easily by the use of higher design stress levels. In other words, once adequate strength and toughness have been attained to prevent collapse or fracture, a structure may become fatigue-limited quickly.

Among the many variables and aspects that relate to fatigue crack propagation in high-strength alloys, the following points are considered significant.

(1) The concept of nonpropagating fatigue cracks is inapplicable generally to designs employing high-strength structural alloys, except in the context of crack-growth retardation due to periodic overloads. The apparent ΔK threshold levels for nonpropagating cracks observed in high-strength alloys appear exceedingly low (in the range of 3 to 10 ksi $\sqrt{in}$ for all materials). These threshold levels (Region I, Fig. 7, Appendix C) indicate that the allowable flaw sizes for high-strength alloys are extremely small.

(2) Under conditions of stable fatigue crack propagation (Region IIC, Fig. 7, Appendix C), the maximum difference in crack-growth rates for a given alloy, or

family of similar alloys, is approximately a factor of 5 in the absence of an aggressive environment. These differences are of sufficient magnitude to deserve exploration and exploitation but of insufficient magnitude to change the nature of the problem, as can be achieved in improving fracture characteristics from brittle plane-strain behavior to more ductile elastic-plastic behavior through metallurgical quality. High-toughness alloys tend to fall along the favorable side of the da/dN-ΔK scatter-bands for any given family of alloys. However, in many instances, the relative order of merit among competing alloys does not correlate with any of the mechanical properties. Particularly in nonferrous alloys, specific differences in fatigue crack-propagation behavior are not well understood and, therefore, are difficult to reproduce in various samples of the same basic alloy.

(3) The phenomenon of very high rates of fatigue crack growth under high-amplitude cycling (See Region II of Fig. 7, Appendix C) appears to occur in all high-strength alloys regardless of fracture-toughness characteristics. Recognition of this phenomenon may require severe limitations on the allowable cyclic stress-intensity levels in service even for the best available high-strength alloys.

(4) Among the multitude of variables, commonly cited in relation to fatigue-crack propagation, several are of limited significance. Stress state (i.e., plane-strain or plane-stress) and thickness do not appear to have

major effects on crack-growth rates. Probably, frequency is not an important factor, except where aggressive environments are involved. Test-specimen geometry often does not influence da/dN-ΔK crack-propagation data.

(5) The two most important areas of fatigue crack-propagation behavior that are not understood well are complex spectrum loading and environmental effects. The analysis of fatigue crack propagation under complex loading is an infant technology, although crack-growth retardation resulting from peak loads is understood to have an extremely beneficial effect on fatigue life. The only recourse currently available for design estimates of fatigue life is to reproduce or simulate actual service loads in laboratory studies.

(6) Environmental effects, particularly corrosion-enhanced crack propagation, are similarly difficult to predict, although laboratory studies can reveal worst-case limits of behavior. In the absence of stress-corrosion cracking, recent studies have shown that the maximum effect of environment tends to occur at frequencies in the range of a few cycles per minute and that crack growth rates are influenced by the rate of rising load application rather than by the duration of the hold time under load.

b. Recommendations

(1) It is recommended that the mechanisms of cyclic crack growth, particularly in service environments, be studied to understand the influence of metallurgical factors and that these findings be translated into improved alloys and processing schedules.

(2) It is recommended that the nomenclature for fracture mechanics be standardized.

A serious problem has evolved from the proliferation of nonstandard and/or scientifically questionable nomenclature, such as K_X, K_{IH}, etc. In many cases, the "K" terminology is assigned to crack-tip conditions that are not definable by elastic stress fields. As a result of such practices, a large portion of the literature is complicated and confusing and may be even misleading.

A standard designation, such as J_c or other appropriate terminology, should be evolved for crack-tip conditions above the limits of K_{Ic}, and this designation should indicate to the engineer-user of the information that K stress fields are not implied by the property measurement. The appropriate ASTM Committees and MIL-Handbook-5 Committees are recommended for this task.

E. Nondestructive Evaluation

1. General

In the broad sense, nondestructive evaluation refers to the many different inspection and evaluation procedures that can be applied to a material from its molten state through all fabrication operations from mill processing through installation of the finished part on the completed aircraft.

However, this discussion will be confined to NDE as applied to the detection and evaluation of cracks or crack-like flaws.

NDE plays a critical role in any fracture-control program. With increasing demands for high performance combined with high reliability, greater dependence is placed on NDE for the elimination of flawed parts during manufacture and for the early detection of critical defects in service. Ideally, NDE should determine not only the flaw size but also its shape and should do this reliably for extremely small defects. Today, the state of the art is far short of this goal and, in fact, the sensitivity limits of the various NDE procedures have not been well established in terms of crack detection. Designers always should choose materials and stress levels that assure high reliability under most conditions.

2. <u>Current NDE Methods</u>

Current NDE methods in wide use are:

a. visual inspection, including the use of optical aids;

b. dye penetrant;

c. magnetic particle;

d. radiography, including gamma rays;

e. ultrasonic pulse echo; and

f. eddy current and electro-magnetic induction.

Guidelines for the application of these techniques are discussed in Appendix D and summarized in Figure 20.

a and b. <u>Visual Inspection and Dye Penetrant</u>. Visual inspection and dye penetrant are particularly well-suited to the location of surface-connected flaws. Part geometry is relatively unimportant but the surfaces must be accessible and clean. Etching of the surface preceding visual

or penetrant inspection often is necessary to remove smeared metal. The etchants used, or in some cases the penetrant fluids themselves, possibly could promote crack extension during subsequent loading. The most careful washing procedures probably would not remove all traces of these fluids and the possibility of stress corrosion should be investigated by suitable tests with cracked specimens.

c. Magnetic Particle. Magnetic particle inspection is useful in detecting surface and near-surface flaws provided the material containing the flaw is ferromagnetic. Films or thin coatings do not affect significantly the performance of this method.

d. Radiography. X-ray and gamma-ray radiography are used widely for the inspection of heavy sections. Under ideal circumstances, the size and shape of flaws can be determined by examination of the radiographic film. While radiographic techniques are adaptable to a wide variety of part shapes and sizes, the interpretation of their film can be quite difficult in situations where the structure has varying density, such as in weldments of complex alloys.

e. Ultrasonic Pulse Echo. Ultrasonics are particularly useful for detecting buried flaws although the technique is equally suitable for detecting surface-connected defects. An acoustic couplant is required between the part and the transducer. Coupling may be obtained through the oil film or by immersing both the part and the transducer in a water bath. In either case, checks should be made to determine the possibility of stress-corrosion cracking during subsequent loading due to the presence of residual oil or water in surface cracks. Inspection of complex metallurgical structures may pose special

difficulties due to spurious reflections from segregated phases and grain boundaries.

f. Eddy Current and Electromagnetic Induction. Eddy current and electromagnetic induction are special techniques. They are best suited to the inspection of relatively simple parts. The probes may be tailored easily to the geometry and where past experience can establish that indications are due to flaws and not to metallurgical nonuniformities, such as the presence of retained austenite in a ferritic matrix.

3. Sensitivity of Current Methods

To arrive at rational judgments about the reliability of NDE procedures, adequate information must be available concerning their sensitivity to cracks and crack-like flaws. As yet, such information is available only in a very general form, and no standards have been established that relate specifically to crack detection. In fact, the conventional methods of calibrating NDE equipment involve the use of discontinuities that bear little relation to cracks. For example, ultrasonic pulse-echo equipment is calibrated using blocks containing flat-bottomed holes (ASTM E 317-68).

A systematic study was made recently of the ability of several NDE methods to locate, identify, and measure fatigue cracks of various sizes in cylinders (Packman, et al., 1969). The results, discussed in Appendix D, showed that radiography was a much less discriminating technique than penetrant, ultrasonic, or magnetic particle inspection methods in respect to crack-detection sensitivity (ratio of number of flaws found to the actual number) and the accuracy of crack-shape identification. However, none of the methods showed

sensitivities better than 60 percent for cracks 0.10-inch long (about 0.05-inch deep) or less. In view of these results it appears that the reliability of present NDE methods in locating and characterizing cracks that could cause catastrophic failure in structures made from ultra-high-strength materials is not satisfactory. Furthermore, the cracks examined in this study were produced in tension-tension fatigue and probably were not as tight as cracks produced in reversed bending or a flaw under compressive residual stress, such as a lack of penetration in a weldment.

4. Application of NDE

Experience has shown that crack-like flaws can be introduced into the metal at various stages of processing from breakdown of the initial ingot to assembling the finished structure. In addition, cracks can be generated during use of the structure due to the action of repeated loads and/or environmental effects. Various problems that are associated with the application of NDE procedures to metal processing and to assembly of finished parts are discussed in Appendix D, and the use of a combination of methods is emphasized for many cases. Inspecting forging stock for damaging segregations is particularly important. For example, titanium alloys can contain low-density inclusions that act as low-energy fracture paths. There are many opportunities to introduce cracks or crack-like flaws during assembly operations. If welding is involved, cracks or areas of nonpenetration may be under high residual compression stress and are particularly difficult to detect. Improperly prepared Taper-Lok or other close-tolerance holes are excellent sources of cracks that are impossible to find in an inaccessible finished assembly. The problem of accessibility for NDE should

be considered during the initial stages of design. The development of techniques for the inspection of structure in service aircraft is one of the most challenging problems in the field of NDE. Techniques are needed that can be used reliably in assemblies where access is far from optimal and frequently is hampered by the presence of sealants, paints, etc. Disassembly is undesirable because of the cost and possibility of damage during disassembly and subsequent reassembly.

5. Conclusions and Recommendations

a. Conclusions

(1) NDE techniques, when applied to the detection and evaluation of cracks or crack-like flaws, are an indispensable part of a fracture-control program. Their importance increases as the strength level of the material and the structural loads increase.

(2) At present, users know only roughly the sensitivities of the various NDE procedures as applied to finding cracks or crack-like flaws. However, available information indicates that even the best production techniques, in some cases, are incapable of locating cracks that are of sufficient size to cause failure of highly loaded structures made from the strongest alloys. Furthermore, catastrophic failures of aerospace and aircraft structures have been caused by the presence of flaws that were definable readily on the fractured surfaces and appeared large enough to have been detected by conventional NDE methods. In another case (Appendix D), the fracture origin was not a crack in the accepted sense but a weak region associated with metallurgical damage and probably could not have been detected by any known NDE technique.

(3) Generally, standards used to calibrate NDE equipment are incapable of representing crack and are not useful as training aids for qualifying NDE operators. As might be expected, the detectability of cracks can be enhanced by the application of loads that tend to open them. For this reason, it may be desirable sometimes to combine conventional NDE procedures with a proof or other loading procedure test. For some aircraft applications, where a proof test may be desirable, a structure must be designed with the proof test in mind. Such design results in a significant weight penalty, which is generally not acceptable.

(4) Apparently, to achieve high reliability in advanced performance aircraft, NDE must be considered from the early stages of conceptual design to assure the accessibility and reliability of NDE inspection of critical structural areas during manufacture and for service maintenance of the aircraft.

b. Recommendations

The areas listed below should be given priority in NDE research and development:

(1) Accumulation of data on the following variables to establish standards for crack detection by NDE:

(a) crack shape and size,

(b) crack tightness;

(c) matrix structure, e.g., welds and parent metal,

(d) alloy type, and

(e) crack-like flaws, such as lack of weld penetration.

(2) Establishment of required NDE standards with the assistance of an ASTM Task Force formed for that specific purpose.

(3) Investigation of methods by which NDE procedures may be combined with proof testing without a significant weight or cost penalty.

(4) Establishment of information- and data-dissemination services for NDE procedures and results of failure analysis involving NDE.

(5) Use of NDE in a more cost-effective manner particularly since NDE costs can be as much as 10 to 15 percent of the manufacturing cost of a complete aircraft or can exceed the manufacturing costs of individual components. In many instances, the use of NDE procedures (with continuous feedback) during the processing of components reduces their fabrication costs by improving reliability and manufacturing procedures and by reducing repairs, rejects, and final inspection costs. Expensive, time-consuming NDE techniques should be focused primarily on critical components and structural areas where defects might lead to catastrophic failure. Whenever possible, these critical components and areas should be delineated in the early design stages when their material, fabrication, and inspection requirements may be established.

(6) Improvement in material quality and fabrication procedures, such as forming, machining, and chilling, to reduce or eliminate significant impurities and flaws, thereby increasing the reliability of the components and structures.

(7) Motivation of workers and management to achieve the objectives of the NDE program in a fracture-control plan.

F. Requirements for Advancement of Basic Technology

The Committee perceived close relationships in the advancement of the technological bases for metals and for structural design. Basic engineering principles that dictate criteria for metals selection also serve to define directions for improvements of high-strength metals. These principles apply generally to all structures and all families of structural metals and make a strong case for the broad advancement of the technological base that determines design practices. However, the tendency today is to restrict funding for technological advances to specific system and/or "platform" requirements. This trend, reflecting the thesis that the technological base is specific to systems, is in sharp contrast to precepts of generalization of structural design capabilities.

The following case is presented for advancement of the technological base on broader, rather than narrower, fronts:

1. System concepts and preliminary designs must be fixed in relation to existing technology.
2. Once fixed, neither time nor flexibility exists for major redesign adjustments resulting from technological advancements.
3. Trade-off analyses and design competition cannot be based on visionary estimates of projected improvements.
4. Technology extrapolations may be dangerous because, all factors considered, competition tends to foster overestimates.

The case history of broad-front improvements in metal properties across the most critical strength range of steels and titanium alloys documents the vagaries of predetermination

of a platform basis. In several cases, developments that were intended for one purpose offered the best promise for other applications, specifically for high-performance aircraft applications. Such experiences indicate the need to consolidate requirements and to fund efforts for advancing the technological base in its own right.

The Committee does not present a case for "random-walk" evolution of technological capabilities in all possible directions; however, it believes that rational directions should be established and supported on a broad, rather than a narrow, basis. Primary needs for broad-front advancement of the technological base include:

1. evolving metals of higher strength levels to feasible limits, with retention of desirable fracture properties;
2. advancing the state of engineering knowledge for definition of fracture properties, particularly for the elastic-plastic case;
3. advancing the technological base for weld-metal properties to higher strength levels with retention of desirable fracture properties;
4. advancing the state of knowledge relating to environmental effects, including test practices, interpretations to structural design, and properties of specific metal systems; and
5. advancing the state of knowledge of fatigue-related questions since capabilities for deterministic fatigue-life design are presently inadequate for any structure that requires such considerations.

Consolidation of requirements and funding the advancement of the basic technologies, which are inferred by the above listing, are considered to be of crucial importance. Specific engineering developments result from basic technological capabilities and are limited to the state of existing knowledge.

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APPENDIX A

COMPUTATION OF CRITICAL CRACK SIZE FOR SURFACE FLAWED COMPONENTS

Computation of Critical Crack Sizes for Surface Flawed Components

Assume the following three components are loaded in axial tension:

(a) A plate 1-inch thick and 6-inch wide

(b) A plate 0.25-inch thick and 20-inch wide

(c) A plate 0.06-inch thick and 80-inch wide

The yield strength and toughnesses of the steel in all three components are:

$$220 \text{ ksi} \le \sigma_{ys} \le 240 \text{ ksi}$$

$$110 \text{ ksi}\sqrt{\text{in}} \ge K_{Ic} \ge 80 \text{ ksi}\sqrt{\text{in}}$$

During service the peak tensile stress, σ, is $\sigma = 0.8\ \sigma_{ys}$. For simplicity of this illustration, only one value of the ratio, $\sigma/\sigma_{ys} = 0.8$ will be used.

For a semi-elliptical surface crack of depth, a, and length 2c, the relationship between toughness, K_{Ic}, stress, σ, yield strength, σ_{ys}, and crack configuration represented by (a/Q), is,

$$\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 = 1.2\ \pi\left(\frac{\sigma}{\sigma_{ys}}\right)^2 \left(\frac{a}{Q}\right) \qquad (1)$$

where Q is a crack-shape parameter. From the material properties and stress listed above:

$$0.11 \le \left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 \le 0.25$$

and

$$\left(\frac{\sigma}{\sigma_{ys}}\right) = 0.8$$

Appendix A

A graphical representation of Equation (1) is shown in Figure 4. From the range of values of the ratio, $(K_{Ic}/\sigma_{ys})^2$, the range of values of (a/Q) is found to be,

$$0.046 \le \left(\frac{a}{Q}\right) \le 0.1035$$

The flaw-shape parameter Q is given by

$$Q = \Phi^2 - 0.212\left(\frac{\sigma}{\sigma_{ys}}\right)^2 \qquad (2)$$

where Φ is an elliptical integral, a function of a/c, evaluated to give the stress field at the end of the minor axis of the eliptical crack (the location of the highest K_I value). Q is evaluated graphically in Figure 5. For $\sigma/\sigma_{ys} = 0.8$, Q is in the range from 0.87 for a long shallow crack across the surface of a plate to 2.26 for a semicircular surface crack. Four crack configurations, specified by their a/2c values were selected for illustration, for each extreme value of (a/Q) listed above. The dimensions of the critical crack sizes corresponding to these conditions are listed below:

a/Q	a/2c	Q	a, in.	2c, in.
0.106	0	.87	.092	∞
	.1	.96	.102	1.02
	.33	1.60	.169	.507
	.5	2.26	.239	.478
0.049	0	.87	.043	∞
	.1	.96	.047	.47
	.33	1.60	.079	.236
	.5	2.26	.111	.222

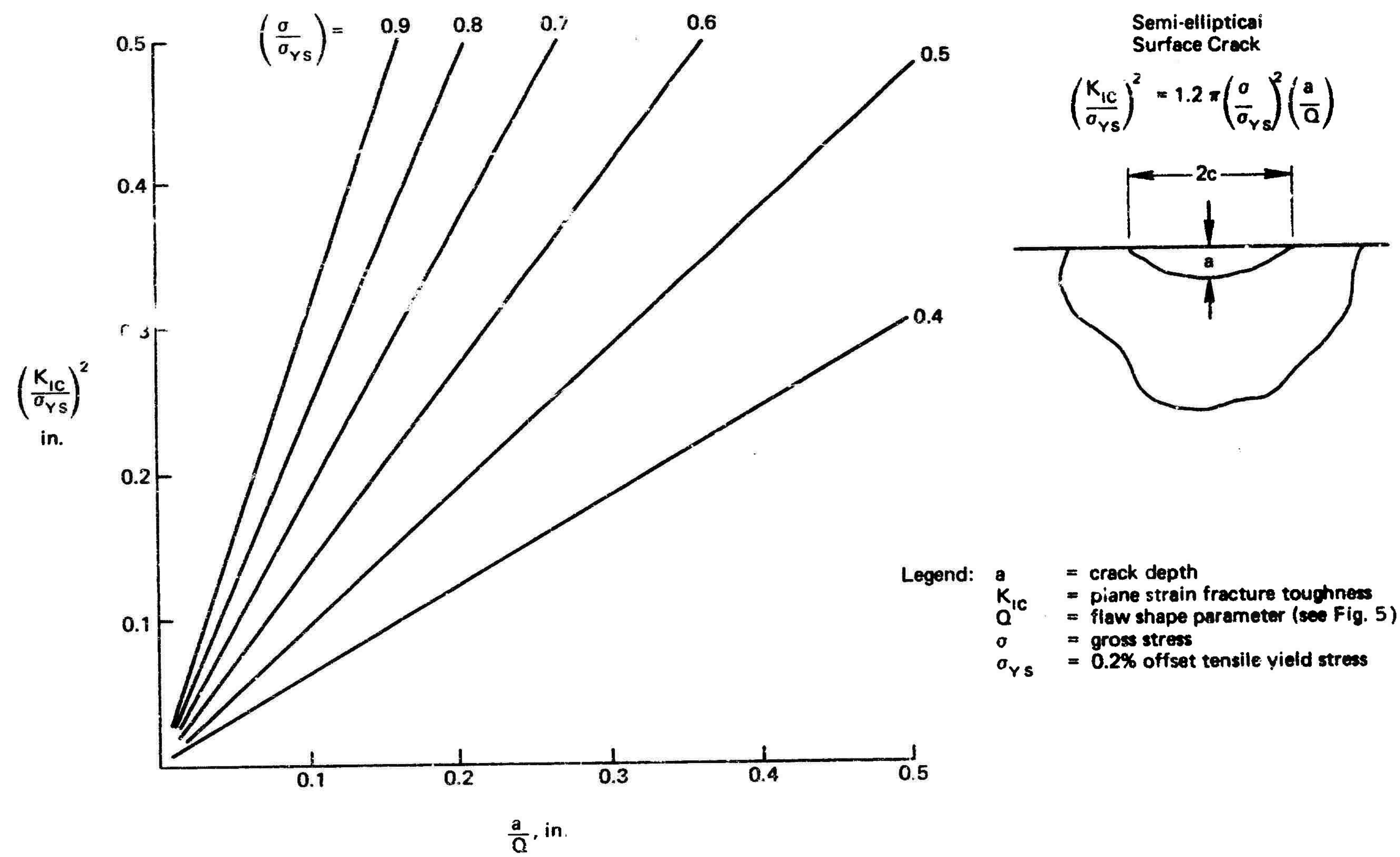

FIGURE 4. Relationship of Toughness, Stress, and Crack Configuration.

Source: Irwin, 1962.

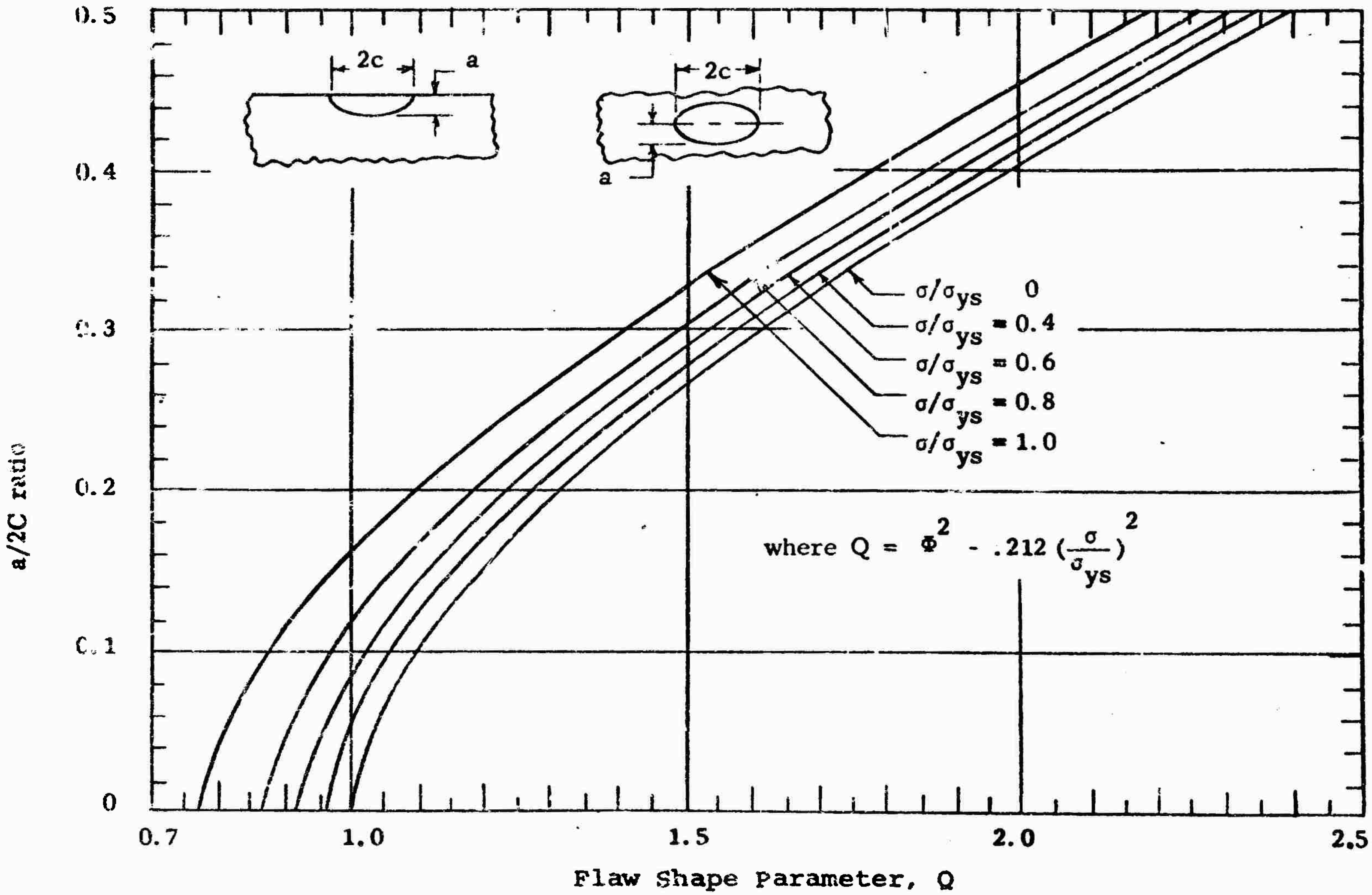

FIGURE 5. Flaw Shape Parameter Curves for Surface and Internal Cracks.

Source: Tiffany and Masters, 1964.

The specimen size requirements specified by ASTM to insure measurement of K_{Ic} (to develop sufficient transverse constraint to obtain a minimum toughness, K_{Ic}, independent of thickness) are,

$$\left.\begin{matrix} a \\ B \end{matrix}\right\} \geq 2.5\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 \tag{3}$$

For the range of allowable yield strengths, the minimum specimen thicknesses are listed below:

σ_{ys}, ksi	$(K_{Ic}/\sigma_{ys})^2$, in.	Min. Thickness, B, in.
220	0.25	$B \geq 0.62$
240	0.11	$B \geq 0.28$

Either of two plane strain specimens, the bend specimen or the compact tension specimen, has been qualified by ASTM to give reproducible values at K_{Ic} when the size requirements, Equation (3) plus other conditions are satisfied.

A plot of $(K_{Ic}/\sigma_{ys})^2$ versus the specimen thickness, B, is illustrated in Figure 6. For a valid K_{Ic} measurement, the specimen thickness must be greater than that indicated by the line labeled $\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 = \frac{B}{2.5}$. For the three components in this example problem, only the 1-inch-thick component is of sufficient thickness to provide the plane strain state of stress required for valid K_{Ic} values. The 0.06-inch-thick sheet would fracture in a plane stress mode, with large amounts of plastic

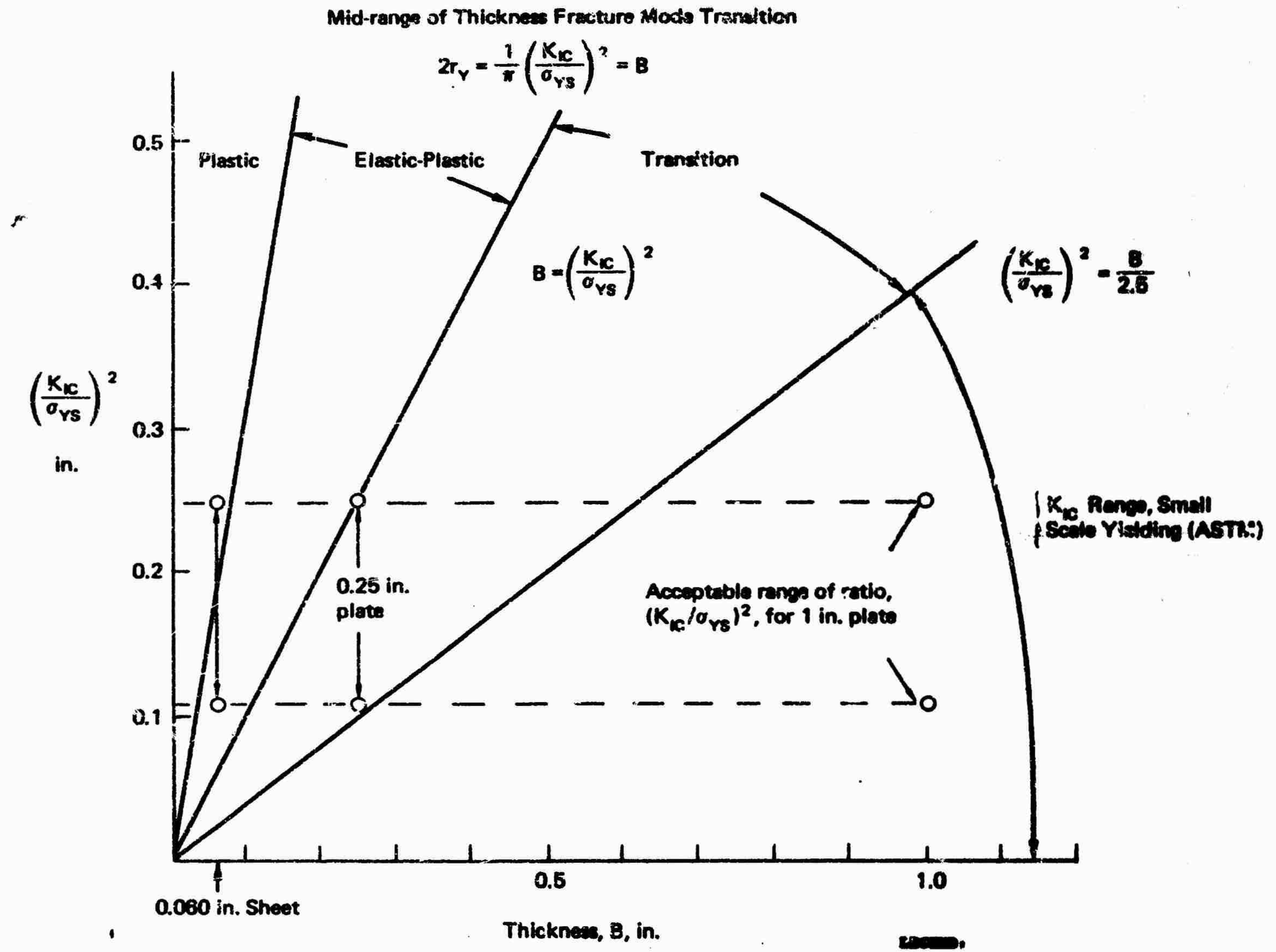

FIGURE 6. Effect of Thickness on Fracture Mode.

Source: Naval Research Laboratory

LEGEND:

B = thickness

K_{Ic} = plane strain fracture toughness

r_y = plastic zone radius

σ_{ys} = 0.2% offset tensile yield stress

deformation taking place at failure. A transition-mode or mixed-mode type of failure would occur for the 0.25 inch thick plate.

For structural components containing semi-elliptical surface cracks, no size requirements have been established. From experience, however, the size requirements, specifically the thickness, B, are known to be equal at least to the specimen size. Thus for this illustration, the specimen size requirement thickness has been used as a lower limit on the component size for which K_{Ic} is an appropriate toughness. The K_{Ic} values given at the beginning of this appendix (110 ksi $\sqrt{in} \geq 80$ ksi $\sqrt{in}$) are therefore only valid for the 1-inch thick plate and do not adequately represent the toughness of the 0.06- and 0.25-inch thick plates. Consequently, the critical crack sizes given above for four crack shapes are only accurate for the 1-inch thick plate.

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APPENDIX B

FRACTURE TOUGHNESS

CONTENTS

Fracture Toughness

1. Introduction

Fracture mechanics provides terminology to characterize and describe the behavior and crack-like flaws in structures. The crack extension behavior of interest is "onset of rapid crack extension." The corresponding structural behavior ranges from a significant reduction in the load-carrying capacity of a member to its complete separation.

The fracture-mechanics approach is based on an analysis of the crack-tip stress and strain field. In the range of small-scale yielding, linear elastic-stress analysis indicates that the crack-tip stress field is unique, that is, the stress distribution that is close to the crack tip but outside the tiny plastic zone is the same for a sharp crack in all geometric configurations for Mode I (opening) loading. The elastic stresses are proportional to a single parameter, K, the stress-intensity factor. The stress-intensity factor, K, in turn, is the product of the remotely applied stresses (or loads), the square root of the flaw size, and a dimensionless geometry factor of magnitude close to unity.

By using a cracked member under increasing load, the resistance offered by the material to crack extension is determined as the K value corresponding to the onset of rapid crack extension. This critical value of K, denoted as K_c, is a single parameter that measures the resistance of the material to rapid crack extension and frequently is called the fracture toughness. Whenever the K value characterizing the crack-tip stress field

in a flawed structure approaches K_c, onset of rapid crack extension in the structure is imminent.

For elastic behavior, the crack-tip stress field and crack extension behavior can be described equally well in terms of strain energy. An equivalent description that actually preceded the crack-tip stress analysis, K, description is given in terms of the strain-energy rate, $\mathcal{G}$, associated with an increment of crack extension. Under increasing load, the value of $\mathcal{G}$, associated with onset of rapid crack extension is denoted $\mathcal{G}_c$. For plane-stress conditions, the relation between $\mathcal{G}$ and K is: $K^2 = E\mathcal{G}$, where E is Young's modulus. In plane strain, this relation is modified to $K^2(1 - \nu^2) = E\mathcal{G}$, where ν is Poisson's ratio.

Observed crack extension behaviors range between two extremes. At one extreme, onset of rapid crack extension is abrupt, clearly defined, and coincides with the maximum load that a member can carry; the separation is flat and normal to the tensile load. This behavior is observed most clearly in thick members made of low toughness material. At the other extreme, small increments of "subcritical crack extension" occur under increasing load; crack extension is initiated repeatedly and arrested.

Associated with subcritical crack extension and presumably the cause of the "arrest" is the development of an enlarged plastic zone, primarily due to diagonal (45° to tensile load) yielding and the development of "shear lips" due to a change from "flat" to "slant" fracture separation near stress-free surfaces. With increasing load, several increments of subcritical crack extension may occur. Onset of rapid crack

extension occurs when the increase in the crack-tip stress field measured by the K factor (increase in K due to increasing nominal stress and crack length), equals and exceeds the increase in resistance to crack extension (due to an increase of the plastic zone size, crack-tip blunting, and a change from flat to slant separation). This behavior is observed most clearly in relatively thin plates made of high-toughness material.

Many structural metals exhibit crack-extension behavior that lies between these extreme behaviors. In engineering applications, the need for metals of high toughness frequently focuses attention upon the region of complex behavior involving subcritical crack extension.

2. Small-scale Yielding, Full-transverse Constraint: K_{Ic} Plane-Strain Fracture Toughness

The development of fracture mechanics to its present state of the technology has progressed necessarily from the description of the simplest phenomena toward the more complex. Onset of rapid crack extension occurs in an abrupt manner when the plastic zone size is small compared with both the crack length and the thickness and qualitatively describes the conditions for measuring plane-strain fracture toughness, K_{Ic}, which has been standardized by ASTM Committee E-24. In this region, linear-elastic stress analysis, specifically the stress-intensity factor (K), provides a single parameter description of the crack-tip stress field. Consequently, the critical value, denoted as K_{Ic}, also provides a single parameter measure of fracture toughness. According to ASTM, the quantitative requirements for K_{Ic} are designed to achieve the following conditions:

a - ensure that the plastic zone size is small compared to both the crack length and specimen thickness by the specification that a and B $\geq 2.5\ (K_{Ic}/\sigma_y)^2$,

b - ensure that a prescribed increment of crack extension occurs from a sharp crack (fatigue cycling requirement), and thus

c - ensure that a minimum value of toughness has been measured.

3. Large-scale Yielding, Full Transverse Constraint: δ_{Ic} and J_{Ic}

Adding complexity one step at a time, consider a member of sufficient thickness to maintain full transverse constraint (over the central core of a plate away from the stress-free surfaces) as the plastic zone size approaches and finally exceeds the crack size. Under these circumstances, the load-deflection curve deviates from linearity and may approach a nearly constant load "round house" type curve. However, onset of rapid crack extension often remains abrupt and provides a well defined measurement point. Since linear elastic small-scale yielding stress analysis is valid no longer, a new parameter is needed. A complete analytical crack-tip stress analysis (Mode I) for the range of large-scale yielding and fully plastic behavior is unavailable at this time; consequently, it is not completely clear that a unique crack-tip strain field is present. Recent analytical work suggests that due to blunting of a sharp crack the close-in crack-tip stress and strain field may be unique although the distant strain fields are known to be quite different. Further, experimental evidence demonstrates consistent fracture behavior in investigations in which all variables have been carefully controlled. Thus, consistent

with all available evidence, a single parameter is expected to provide an adequate description of toughness when full transverse constraint is maintained.

At this time, several competing descriptions of toughness in the elastic-plastic and fully plastic regions are being investigated. Two descriptions that represent extensions into the plastic range of linear-elastic fracture mechanics will be mentioned.

The concept of "crack opening stretch," denoted by δ (C.O.D.), concerns the opening displacement of the crack faces at the crack tip's elastic-plastic boundary. The "crack-opening stretch," the average of the plastic strains in the crack-tip plastic zone, focuses attention on the close-in crack-tip region. Details furnished by an elastic-strain hardening finite element analysis suggest that the measurement point of δ, the elastic-plastic boundary, is somewhat arbitrary and blurred. Experimental measurements of δ_{Ic} have been most actively pursued in the U.K. Inherent experimental difficulties suggest the need to relate δ to either "crack-tip lateral contraction" or "crack-mouth opening displacement." Investigations along these lines are underway; however, definitive answers are not available at the present time.

A second concept is a generalization of the strain energy rate $\mathcal{G}$ to a nonlinear-elastic material model. The parameter known as the J-integral is identical to $\mathcal{G}$ in the linear-elastic range. J is defined for nonlinear-elastic behavior that is equivalent to deformation-theory plasticity, precluding unloading. In line integral form, J is a path independent parameter that characterizes the close-in crack-tip plastic strain field

and may be evaluated by using the distant plastic strain field or the displacements and forces on the boundary of a member. Simply stated, J promises to be a single parameter description of the crack-tip strain field which may be evaluated either analytically or experimentally. At the onset of rapid crack extension, J_{Ic} becomes a single parameter measure of fracture toughness. Limited data indicate that J_{Ic}, determined from rising load tests of small speciments (full transverse constraint), is equal to $\mathcal{G}_{Ic}$ (computed from K_{Ic}) obtained by using large (ASTM-valid) specimens. Hopefully, experiments currently in progress will confirm the usefulness of J_{Ic} measurements on small specimens for a wide range of conditions of in-plane crack-tip triaxiality (still full transverse constraint) and establish a range of validity and confidence in J_{Ic} as a toughness parameter.

For an elastic perfectly plastic material, J and δ are simply related by $\delta\sigma_y = J$. When strain hardening is included, the relationship is womewhat more complex; however, this relationship suggests two different but related parameters, δ and J, for characterizing the crack-tip strain field.

4. Relaxation of Transverse Constraint, Strain Field Complexities

As the plastic zone size approaches and exceeds the plate thickness, a rather complex crack-tip strain field develops. In addition to the in-plane yielding characteristic of thick (plane strain) members, diagonal (45°) through-the-thickness yielding occurs. This second type of yielding relaxes the triaxial transverse constraint and allows a larger plastic zone to develop and enhance crack-tip blunting. Bursts of flat

subcritical crack extension frequently initiate near the center plane of a plate and tunnel ahead of the crack tips at the surfaces. As loading continues, the surface material separates in 45° slant fracture and shear lips of characteristic size develop.

5. Minimum Transverse Constraint: K_c and Plastic Zone Adjusted Crack Length, $a + r_y$

Possibly, crack-tip deformation for the extreme case of a thin plate is less complex than the intermediate case. For thin plates restrained from buckling, the crack-tip plastic deformation becomes dominantly diagonal (45°) shear and a stress state approaching plane stress ($\sigma_z \rightarrow o$) is developed. In many instances, increments of subcritical crack extension are observed while the plastic zone size is still enlarging. Often a number of increments of subcritical crack extension are observed prior to the onset of rapid crack extension.

When the plastic zone size is small compared with the crack size, the observed values of K_c are sensibly constant (for a given thickness plate) for a variety of member configurations. As the plastic zone size becomes larger, a plastic zone adjusted crack length $(a + r_y)$ has been used to "stretch" linear-elastic fracture mechanics and maintain the value of K_c sensibly constant. When the plastic zone size approaches the length of the crack, net section yielding is impending and linear-elastic crack tip stress analysis is no longer valid.

6. Minimum Transverse Constraint: R Curves

Beyond small-scale yielding but prior to net section yielding, the value of $\mathcal{G}_c$ observed at the onset of rapid crack extension exhibits a systematic trend with crack length and specimen width. This observation led to the concept of

"resistance curves," abbreviated to R curves, as the simplest adequate description of the toughness. R is the value of $\mathcal{G}$ at the beginning and end of each increment of subcritical crack extension. Diagrams of R as a function of crack length obtained for different initial and critical crack lengths suggest that the R curve for plane members is reasonably insensitive to specimen geometry. Thus, the shape of the R-curve is expected to be more of an invariant property of the material (of a given thickness) than the K_c value. By superimposing a diagram of $\mathcal{G}$ (as a function of crack length for a given member) upon a diagram of R (as a function of crack length for a material of appropriate thickness), a point of tangency of the two curves may be determined which corresponds to $\mathcal{G}_c$ for the material and configuration of interest.

One might ask whether $\mathcal{G}$ can be replaced by J in the determination and use of R-curves. The prospects are interesting and intriguing; however, this area remains to be investigated. Subcritical crack extension poses a potential problem that should be investigated.

7. Thickness Fracture Mode Transition

As mentioned earlier in discussing the intermediate range, when the plastic zone size exceeds small-scale yielding conditions and is approaching the plate thickness, the crack-tip strain field is complex. It consists of in-plane as well as diagonal shear (45°) plastic strains. Subcritical crack extension usually is observed. However, the amount may be less than for thin plates. The toughness exhibits a high sensitivity to plate thickness in this region. Below net section yielding a thickness fracture-mode transition occurs from low toughness

K_{Ic} flat separation for thick plates to high toughness K_c slant separation for thin plates. Observed peak values of K_c range from 1.5 K_{Ic} to 3.0 K_{Ic}, although this may not be a maximum for K_c. The midrange of this thickness fracture-mode transition usually occurs when the plastic zone size, r_y, is approximately equal to the plate thickness, B.

8. Toughness Measurements in Transition Range

The methods of characterizing toughness in this range have already been mentioned. K_c employing the plastic zone adjusted crack size probably has received the greatest engineering usage. The crack-opening stretch δ, the J integral, and the R curves each have certain advantages. Each of the methods certainly can provide useful engineering guidance when employed with good judgment. None of these methods have been standardized because complexities and uncertainties exist with regard to each method and insufficient work has been done to establish limits of reproducibility. In this intermediate range, one condition appears essential for each of these methods of toughness characterization: fracture toughness of a material must be measured on a specimen whose thickness is the same as the structural component.

9. Applied Fracture Mechanics: Modeling Thickness, Stress Ratio, and Transverse Constraint of a Structural Component

One useful approach to applied fracture-toughness testing, when standardized measures of toughness and test procedures are unavailable, is to test a "model" simulating the important features of the flawed structural configuration. Using a specimen of the same thickness as the structural component is one

step in modeling. Experience with fracture testing in the intermediate thickness range suggests consideration of several additional features of modeling. Adjusting the specimen crack size in order to approximately match the stress ratio (σ/σ_y) in the test to that encountered in service will further assist in modeling the plastic zone size and other crack-tip deformation complexities. When service-crack configurations produce unusual conditions of constraint, it is desirable to model these constraint features also. Using fracture mechanics to assist in modeling important features has proved highly successful in a number of instances where it has been applied. The obvious disadvantage is that the obtained fracture-toughness value is known to characterize the material only for the specimen configuration used. Apparently, this type of a fracture-toughness testing, assisted by various degrees of modeling, will remain as an important element in the design, development, and verification testing programs for aircraft structures probably for many years.

10. <u>Toughness Measurements Based on Impact Tests: Dynamic Tear Energy for Fracture</u>

Another facet of fracture toughness testing concerns improving metal by process and physical metallurgical control which include melting practice and cleanliness, forming, heat-treating, and welding. Metal-toughness improvement has a significant impact upon the philosophy of the fracture-control planning for all future aircraft. Anticipated improvements in the toughness of steel, titanium, and aluminum alloys are examined in detail in Appendix E, entitled, "Metal Improvement." Over the last decade, considerable toughness data covering a wide range of toughnesses have been used to evaluate "cause and effect" in toughness improvement. For low toughness metals,

K_{Ic} provides a suitable measure of toughness. For very high toughness metals, the toughness has been characterized by both dynamic tear and Charpy impact tests. In these tests, the total energy to fracture the specimen is recorded as a measure of toughness. The dynamic tear tests employ a larger specimen than the Charpy test and have a specimen configuration similar to the K_{Ic} bend specimen, including a sharp crack. Consequently, the results of the dynamic tear test are anticipated to be more closely related to K_{Ic} toughness measurement than Charpy energy values, at least for moderate- and low-toughness metals. K_{Ic} differs from dynamic tear energy as a measure of toughness in terms of the measurement point, transverse constraint (thickness) requirements, and the loading rate. For the high-strength metals of interest for aircraft structures, apparently, the influence of loading rate upon toughness is not very significant. The influence of transverse constraint, however, is significant. Proper interpretation of the dynamic tear-test data (see Appendix E) allows recognition of this influence in a way that appears useful in evaluating the capacity of the metal of a given thickness to be toughened by the occurrence of the thickness fracture-mode transition. When the thickness fracture-mode transition has been identified properly, a region (toughness versus σ_{ys}) exists where the dynamic tear specimen meets the size requirements for the K_{Ic} test. With the measurement point as the only difference between the K_{Ic} test and the dynamic tear test, it appears feasible to establish an empirical correlation between these two measures of toughness. This has been done qualitatively in Appendix E.

APPENDIX C

SUBCRITICAL CRACK EXTENSION

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Appendix C

CONTENTS

SUBCRITICAL CRACK EXTENSION

1. Fatigue Crack Growth

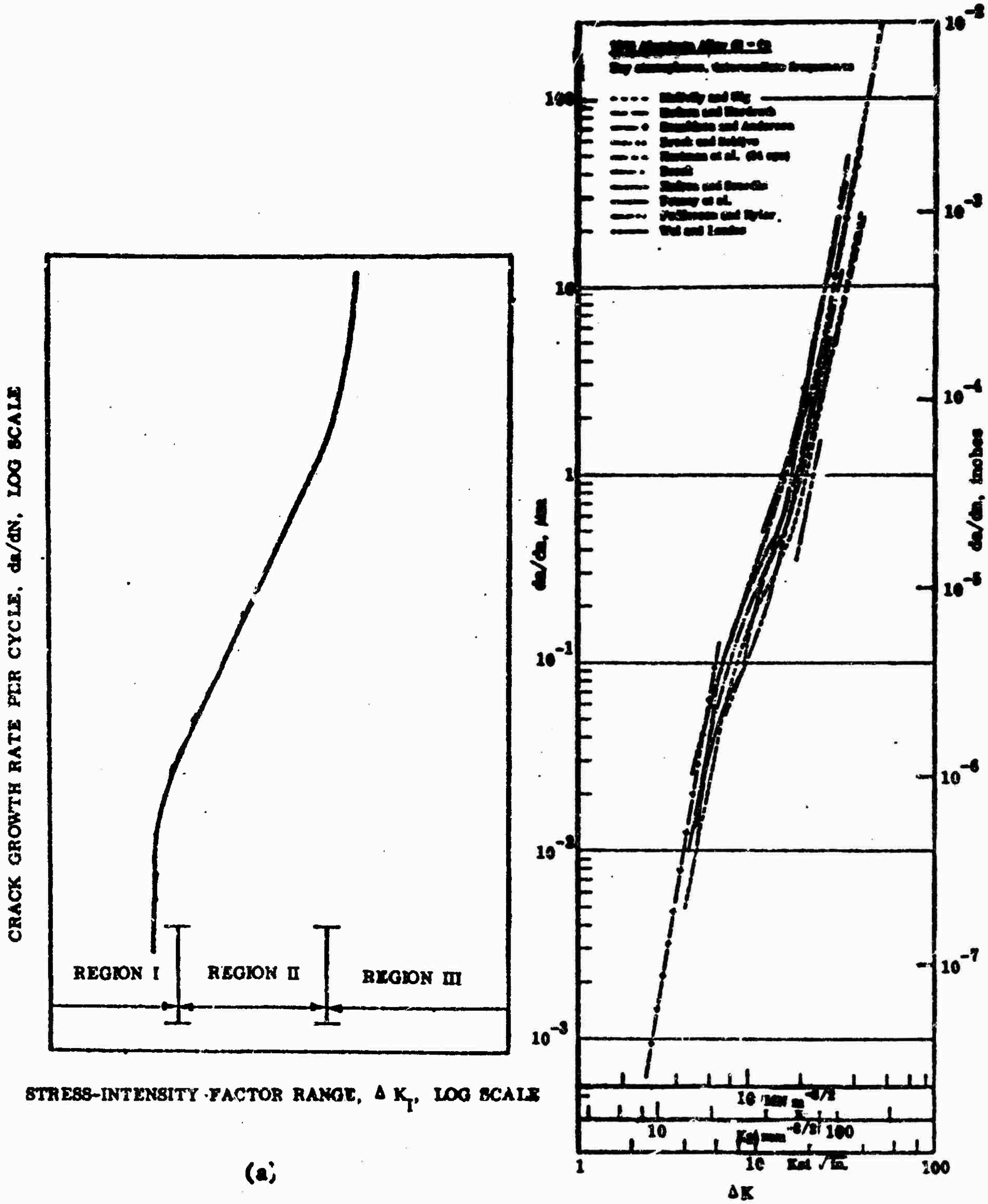
The growth of subcritical size cracks under cyclic loading (Stage II, Fatigue, Fig. 7) involves a large number of variables whose treatment is only now becoming systematized. Included among the variables are:

- the material
- the stress-intensity range
- the stress ratio R
- the corrosivity of the environment, such as the humidity of the air
- cyclic frequency
- loading spectrum
- section thickness
- temperature.

Even under idealized laboratory conditions, e.g., constant load fluctuations and controlled frequency and environment, the description of crack growth involves the three regions of behavior identified in Figure 7.

Region I contains a threshold (ΔK_{th}), similar to the endurance limit of unnotched test bars, below which cracks do not grow under cyclic loading. The characterization of the threshold is complicated by a residual K-value that develops as the crack grows and reduces the applied-K (Eber, 1970).

In the absence of more precise analyses, ΔK_{th} has been approximated by the ΔK-value corresponding to an arbitrarily low growth rate, e.g., $\frac{da}{dn} = 10^{-7}$ in/cycle: $\Delta K_{th} \approx 3\text{-}5$ ksi $\sqrt{in}$ for high-strength steels and $\Delta K_{th} \approx 2\text{-}4$ ksi $\sqrt{in}$ for aluminum alloys (see Fig. 8-b --Hahn and Simon, 1972; Barsom, May 1971).



(a)

FIGURE 7. Cyclic Crack Growth Characteristics for Metals: (a) schematic and (b) compilation of the measurements reported for the 7075-T6.

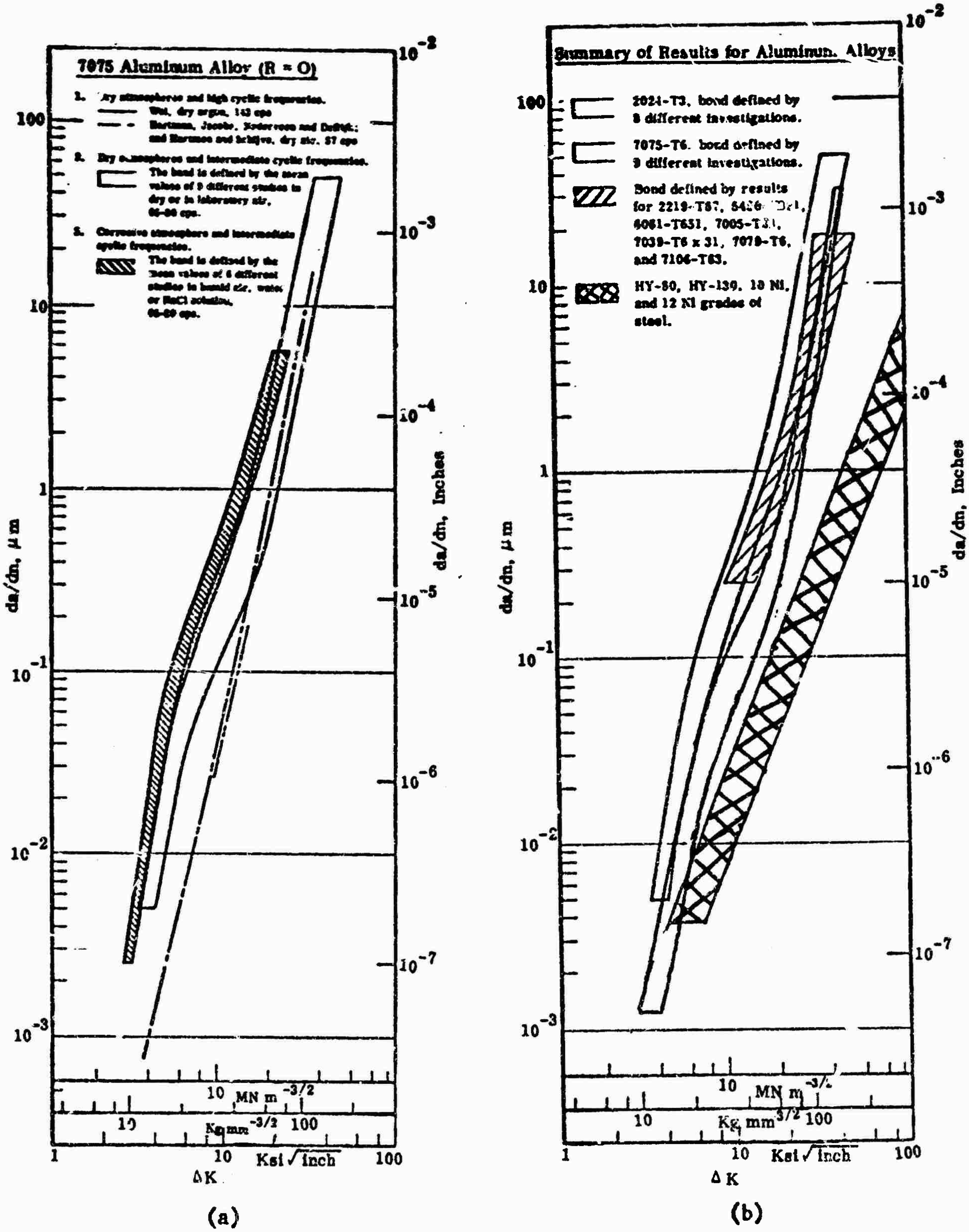


FIGURE 8. Summary of Cyclic Crack-Growth Measurements: (a) influence of environment and cyclic frequency on cyclic growth in 7075-T6 and (b) results for different aluminum alloys and steels.

Source: Hahn and Simon, 1972; Barsom, 1971.

Region II contains the classical fatigue crack growth usually represented by the equation

$$\frac{da}{dn} = Ao(\Delta K)^m$$

where a is the crack length, n, the number of cycles, and ΔK, the stress-intensity range. The coefficient Ao and the exponent m are dependent on the material--composition and heat treatment (See Table 4 and Fig. 8-b)--as well as on the testing conditions, e.g., the stress ratio, test temperature, and the environment. Figure (a) shows that the presence of water or humid air greatly accelerate cyclic crack growth in 7075-T6, and the same is true for other aluminum alloys. Large effects of cyclic frequency in relatively dry environments are probably connected with the reaction time of the underlying corrosion process. Figure (a) illustrates that effects of humid environment and cyclic frequency can alter the crack-growth rate by as much as 20 times.

Region III is the high-stress regime where the peak K-value generated during the cycle approaches K_{Ic} (or K_c)--the critical value for crack extension under monotonic loading. In Region III, growth rates are larger than those predicted by the relation valid in Region II.

Although the growth rate is primarily a function of ΔK, the stress (or stress-intensity) ratio R* has a strong influence also. This has been described empirically (Foreman, et al., 1967), is independent of the form of the $\frac{da}{dn}$ - ΔK relation, and is a useful approximation for both Regions II and III:

$$\left.\frac{da}{dn}\right|_{R=0} = \left.\frac{da}{dn}\right|_{R} \cdot f(R) = f(\Delta K)$$

* R ≡ minimum stress (or stress intensity)/maximum stress (or stress intensity).

TABLE 4. Summary of Room-Temperature Material Parameters for Selected Steel Alloys.

Material	0.2% Yield Strength, ksi	K_{Ic}, ksi $\sqrt{in.}$	Relative Toughness, K_{Ic}/σ_{ys}	n^a	$A_o{}^b$
AISI 1045 steel	37.5	50^c	1.33	4	5.6×10^{-24}
AISI 1144 steel	78	60	0.77	5	3.1×10^{-29}
AISI 4140 steel	65	56	0.83	10	2×10^{-51}
ASTM A533 Grade B, Class 1 steel	68	190^c	2.8	2.2	1×10^{-15}
ASTM A216 WCC grade steel	48	155^c	3.23	3	2.3×10^{-19}
ASTM A469, Class 4 steel	74	90^c	1.22	2.7	4.4×10^{-18}
ASTM A470, Class 8 steel	93	55	0.54	6.7	1×10^{-36}
ASTM A471, Class 4 steel	113	200^c	1.77	1.4	2.9×10^{-12}

[a] n = slope of log da/dN versus log ΔK curve.
[b] A_o = empirical constant from log da/dN versus ΔK data.
[c] Apparent toughness based on extrapolation of existing K_{Ic} data.

where $$f(R) = \frac{(1-R)K_C-\Delta K}{K_C-\Delta K}$$

and K_c is the fracture toughness, and ΔK the stress intensity range. The results of various investigators (Hartman, 1964; Hartman, 1965; Hartman, et al., 1966; Hartman and Schijve, 1970; and Hudson and Scardinia, 1969) involve systematic variations of R and all provide convincing evidence that the Forman, et al., correction is a reasonably accurate description of the influence of the stress ratio both in dry and humid environments. It is similar but not identical to the employed correction (Hartman and Schijve, 1970) that cancels out the singularity at $\Delta K = K_c$.

In principle, the $\frac{da}{dn}$-ΔK curve is a simple and economic device for predicting service behavior.

- The $\frac{da}{dn}$-ΔK curve can be established in the laboratory with a relatively small number of measurements. Figure 7(b) illustrates that such measurements are, in fact, quite reproducible even though the cyclic frequency, air humidity that affects the 7075-T6 alloy, etc., are not standardized.

- Life predictions in the term of "S-N" curves for pre-cracked components can then be derived from the $\frac{da}{dn}$-ΔK curve for any flaw size or shape, component geometry, and stress ratio by way of the integration:

$$n = \int_{a_o}^{a^*} \frac{f(R)}{f(\Delta K)} da$$

where a* is the critical flaw size for unstable fracture. Examples of "S-N" curves calculated for an idealized component:

a 6-inch wide center-cracked panel subjected to cyclic load of constant amplitude, for a number of initial flaw sizes, R- and K_c- values are reproduced in Figure 9. The a_i=1.27 mm (0.050 in) flaw is representative of the lower limit for reliable detection.

In practice, a number of problems are encountered both in predicting the cyclic lifes and in designing structures for specific lifetimes.

Random Loading. In its present form, the analysis is unable to deal with cyclic loading involving large fluctuations in the amplitude of the load cycle. The nature of this problem is illustrated in Figure 10, where isolated overloads show a strong, transient, retarding effect on the subsequent growth produced by lower amplitude cycles. In other words, the contributions of cycles of different amplitudes are not linearly additive. Miner's rule is not valid, and predictions based on the $\frac{da}{dn}$-ΔK curve and a mean amplitude can be highly over conservative. Figure 11 is an example of a "typical stormy-weather flight history" (Broek, 1971). "If the total spectrum is applied, the crack-propagation life in the 2024-T3 material is on the order of 20,000 flights. Omission of the two highest load levels (containing only a few hundred cycles) reduces the life to 10,000 flights." Reliable analytical procedures for compounding the cyclic growth produced by an arbitrary load spectrum from simple $\frac{da}{dn}$-ΔK curves may be developed in the future. In the meantime, accurate predictions of the rate of growth necessitate reproducing the actual load spectrum in the laboratory.

Corrosion Fatigue. As already noted for 7075-T6 (see Fig. 8-a), the joint action of environment and cyclic loading conditions--termed corrosion fatigue--can be extremely degrading

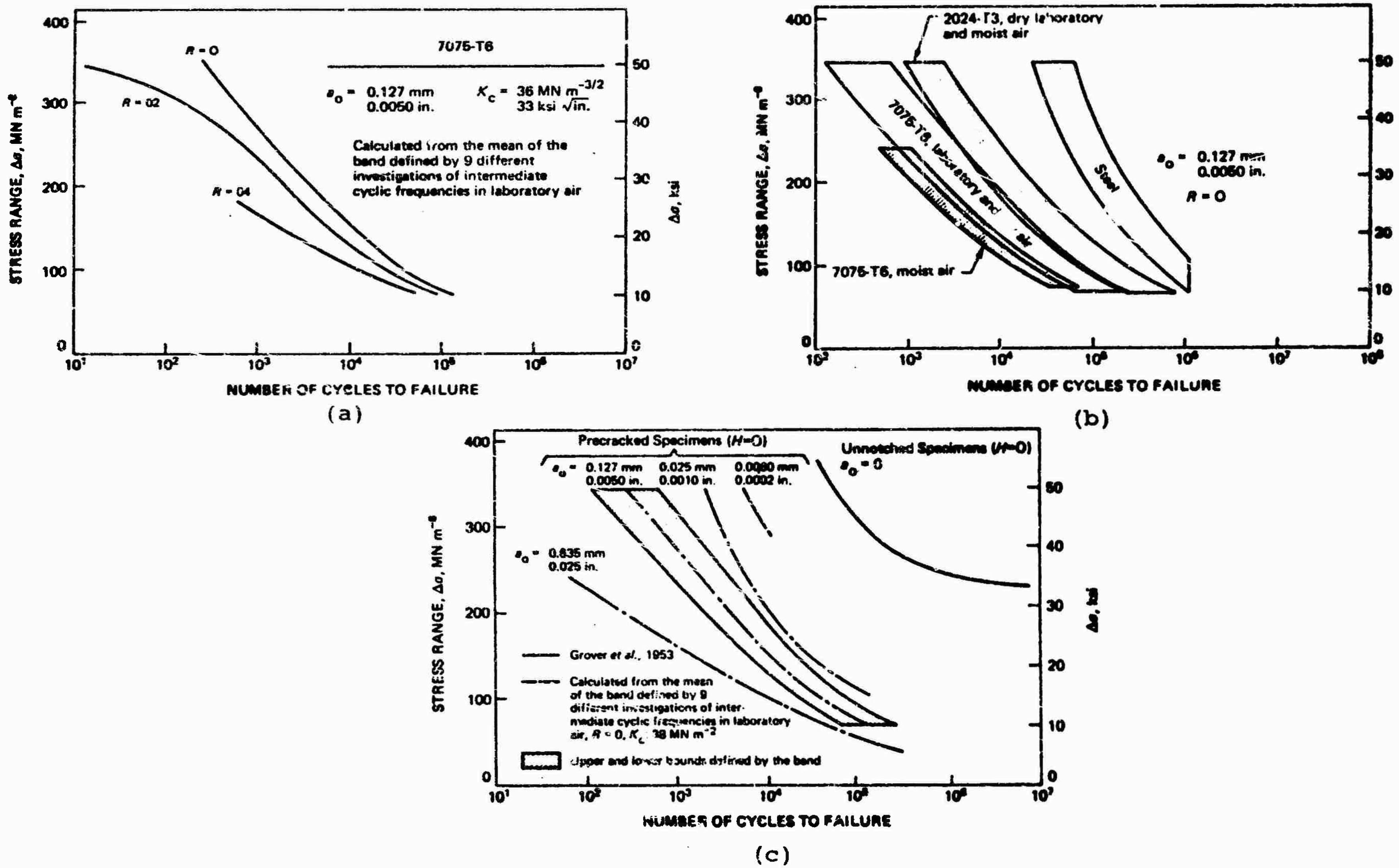


FIGURE 9. Examples of S-N Curves Calculated for a Precracked 6-Inch-Wide Center-Cracked Panel from the $\frac{da}{dn}$ - Δ K Curves of Different Materials: (a) influence of flaw size on 7075-T6, (b) influence of stress ratio and (c) S-N curves for different materials.

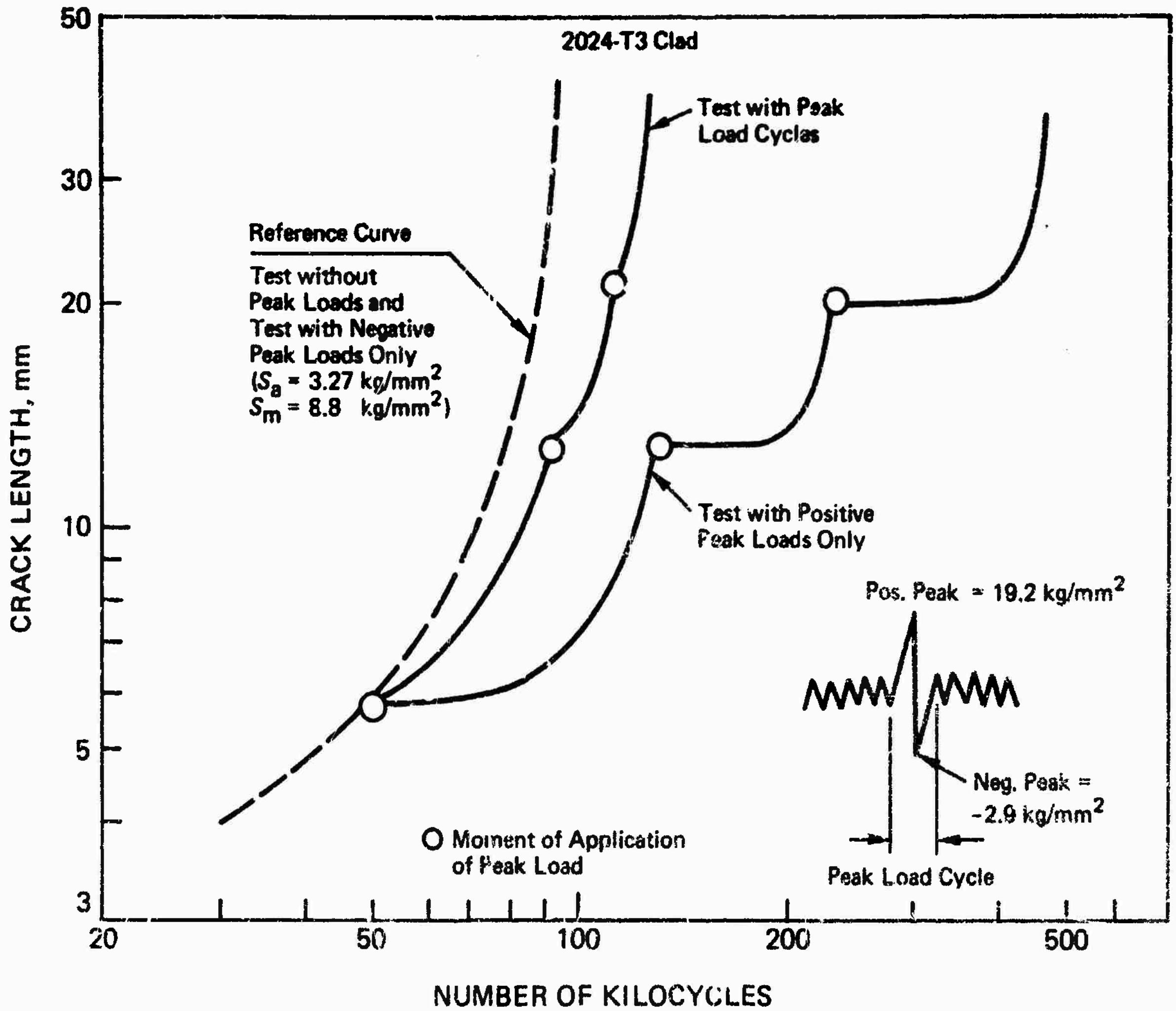


FIGURE 10. Effect of Overload in Constant Amplitude Test.

Source: Broek, 1971.

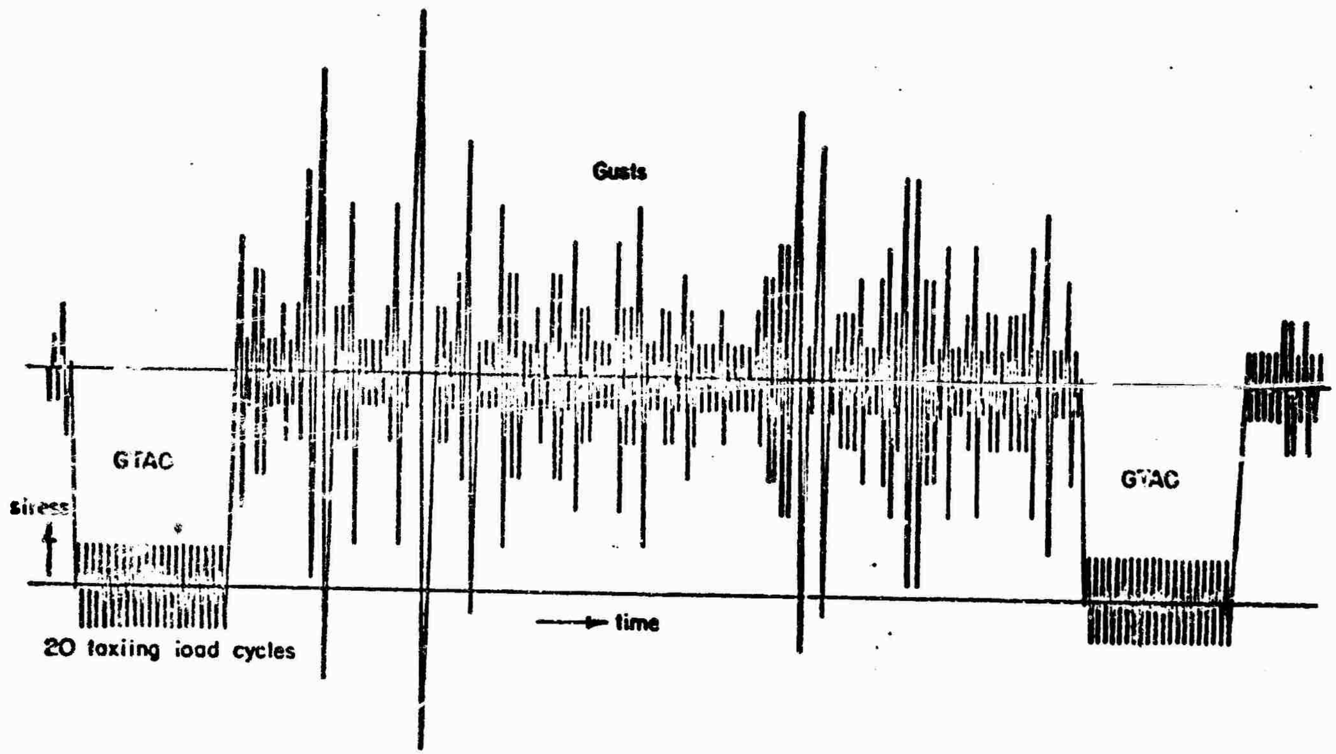


FIGURE 11. Load Spectrum of a "Typical Stormy-Weather Flight History."

Source: Broek, 1971.

to the cyclic life of a material. Corrosion-fatigue action has produced material damage for almost any combination of applied stress level, material heat treatment, and corrosive agent (Wei, 1970; Wei and Landes, 1969; Barsom, 1971). Corrosive environments accelerate cyclic crack growth both above K_{Iscc}* and below this value (Barsom, 1971). Above K_{Iscc}, the mechanism of growth enhancement appears to be similar to that observed under sustained loading. Consistent with this, the corrosion effect becomes more prominent as the cyclic frequency of loading decreases simply because the time under which stress corrosion is operative is maximized. At the same time, analyses of the growth rate, based on a simple linear superposition of the cyclic growth rate and the sustained load-stress corrosion rate, have met with some success (Wei, 1970; Wei and Landes, 1966). The nature of the corrosion contribution below K_{Iscc} may be connected with repeated generation of "clean" surface at the root of the crack which is peculiar to cyclic loading. Consistent with this, the corrosion contribution correlates with the time the test specimen experiences increasing tension loading, i.e., the time the corrosive medium is in contact with clean surface rather than the total time under load (Barsom, 1971). Data for a high-strength steel indicate that the entire crack-growth rate curve is accelerated by sinusoidal or triangular loading where the rate of loading is similar. When a square wave form was used where the loading rate was relatively rapid, no significant corrosion-enhanced crack growth rate was observed.

The uncertain ties associated with random load cycles and corrosive environments mean that not only more tests must be done but the tests must simulate accurately both the loading

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* K_{Iscc} is the stress-intensity range above which stress corrosion crack growth is observed under sustained loading.

spectrum and the service environment. Future studies should concentrate on more efficient test methods and on analytical methods that will reduce the heavy burden of testing.

2. Stress-Corrosion Crack Growth

Subcritical size cracks also grow under sustained loading in the presence of a corrosive environment. Growth rates depend on the K-level, and as in the case of cyclic loading, there is evidence of a threshold K-level called K_{Iscc}, below which no corrosion cracking occurs (Beachem and Brown, 1969; Steigerwald, 1960). Figure 12 illustrates this type of delayed failure curve for 4340 steel. Growth does not begin immediately, but after an incubation period, and is not as continuous as cyclic growth. A typical crack-growth curve, shown in Figure 13, illustrates the incubation period and the generally discontinuous nature of the stress-corrosion cracking. The kinetics of the process can be described by the incubation time, and the crack-growth rate (the crack velocity $\frac{da}{dt}$), stress intensity (K) dependence, as shown in Figures 14 and 15. There are indications that at stress intensity levels close to K_{Iscc} the incubation period rather than the growth rate becomes very long (compare Fig. 15-a and 15-b) and sensitive to prior history; and this is discussed more fully in the next section. The net result is that the crack growth behavior is not always consistent and failure times are often difficult to predict from growth-rate data.

In the case of high-strength steels that are particularly susceptible to stress corrosion, the kinetics of the failure process vary with steel type and strength level (Brown, 1970; Steigerwald, 1969). In certain cases, a straight line

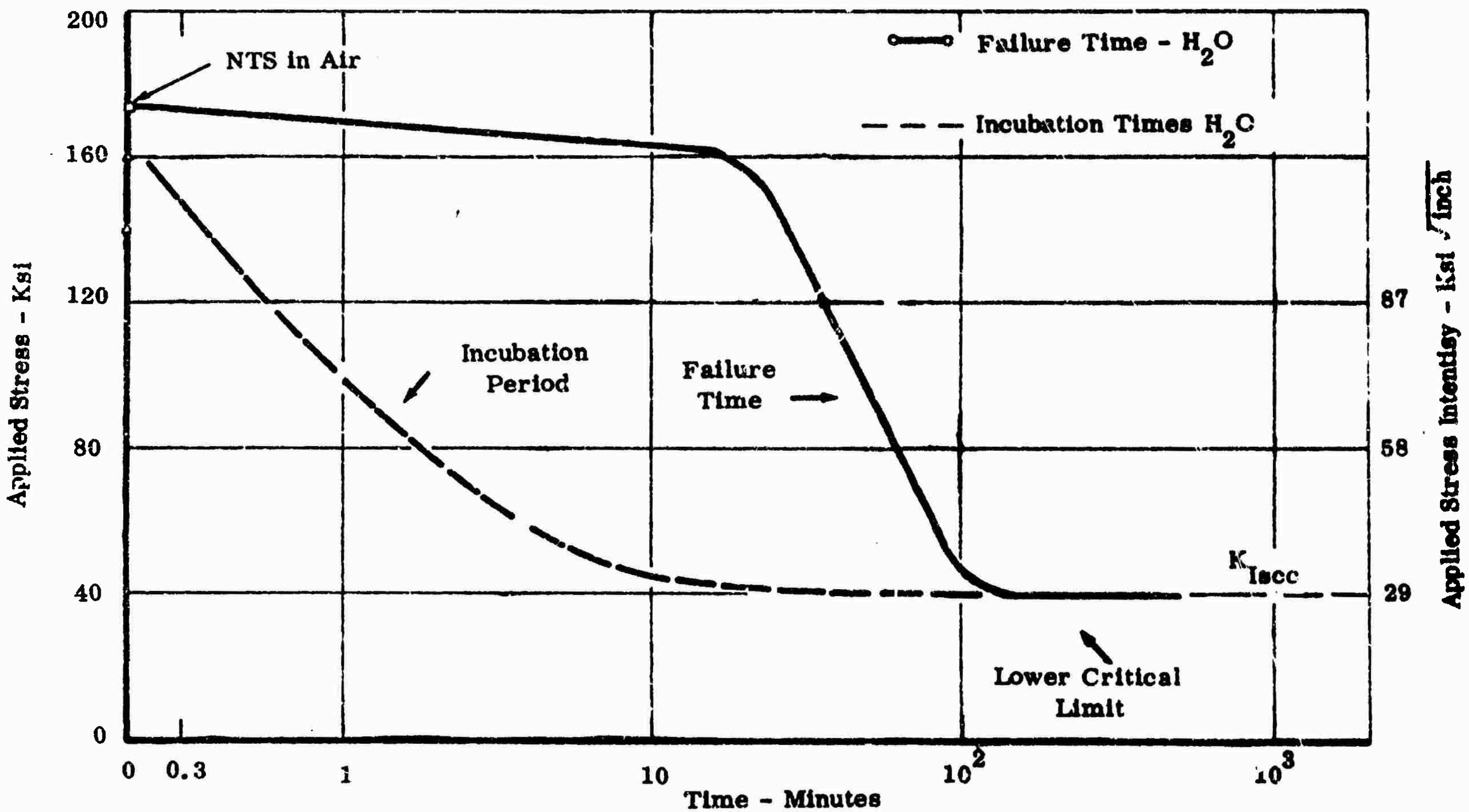


FIGURE 12. Delayed Failure of AISI 4340 Steel (240 ksi strength level) Precracked Sheet Specimens in Distilled Water.

Source: Steigerwald, 1960.

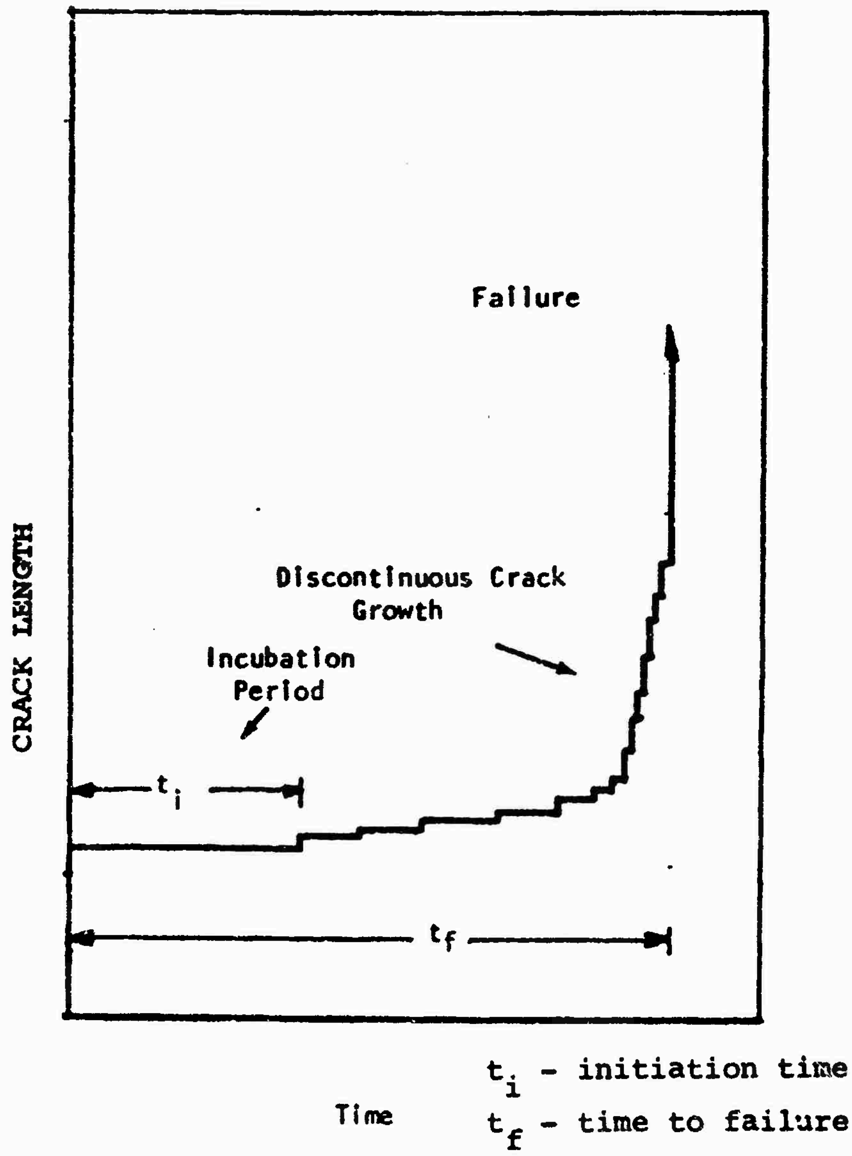
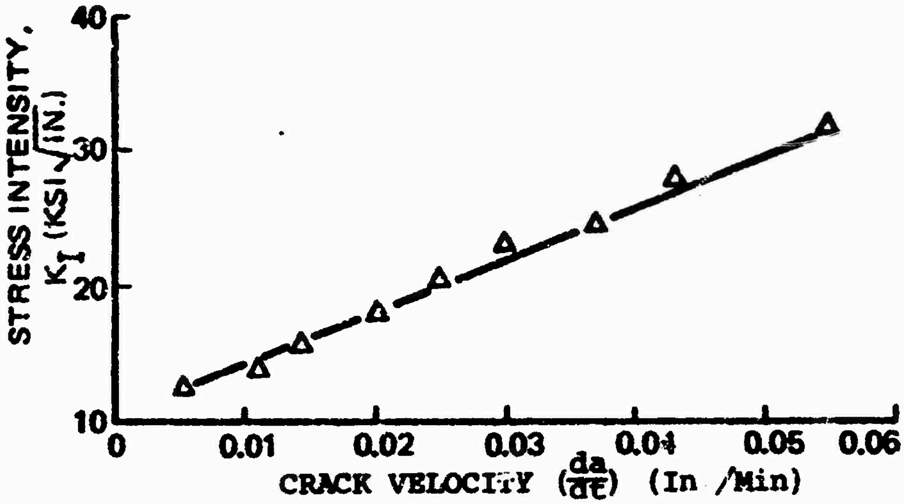
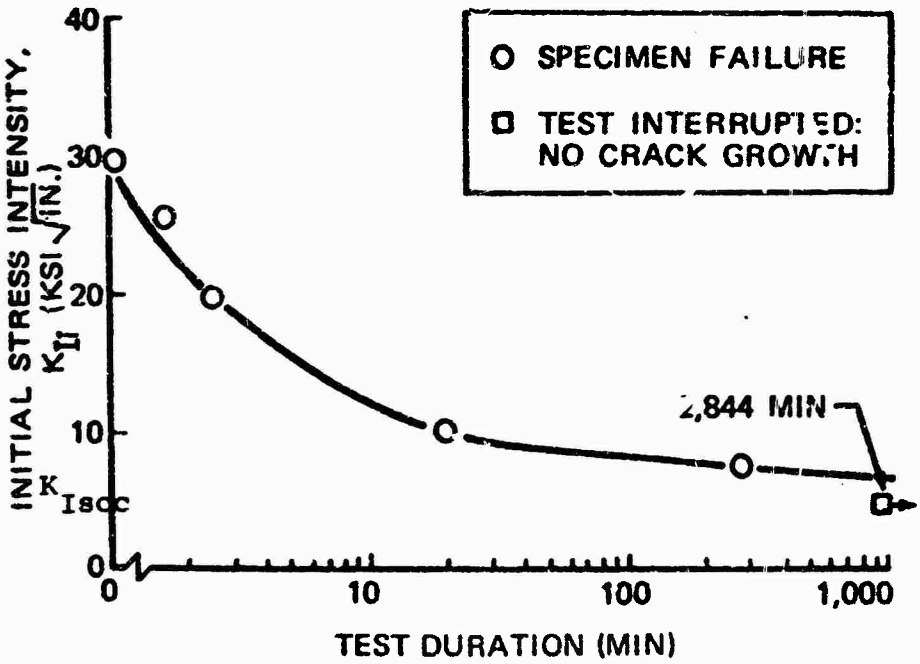


FIGURE 13. Nature of the Discontinuous Crack Growth which Occurs in Stressed High-Strength Steel Exposed to an Aqueous Environment.

Source: Steigerwald, 1960.



a. Velocity curve



b. Stress corrosion curve

FIGURE 14. Comparison of Stress Corrosion and Crack Velocity Curves for 350 Grade Maraging Steel Aged 8 Hours at 800°F.

Source: Carter, 1969.

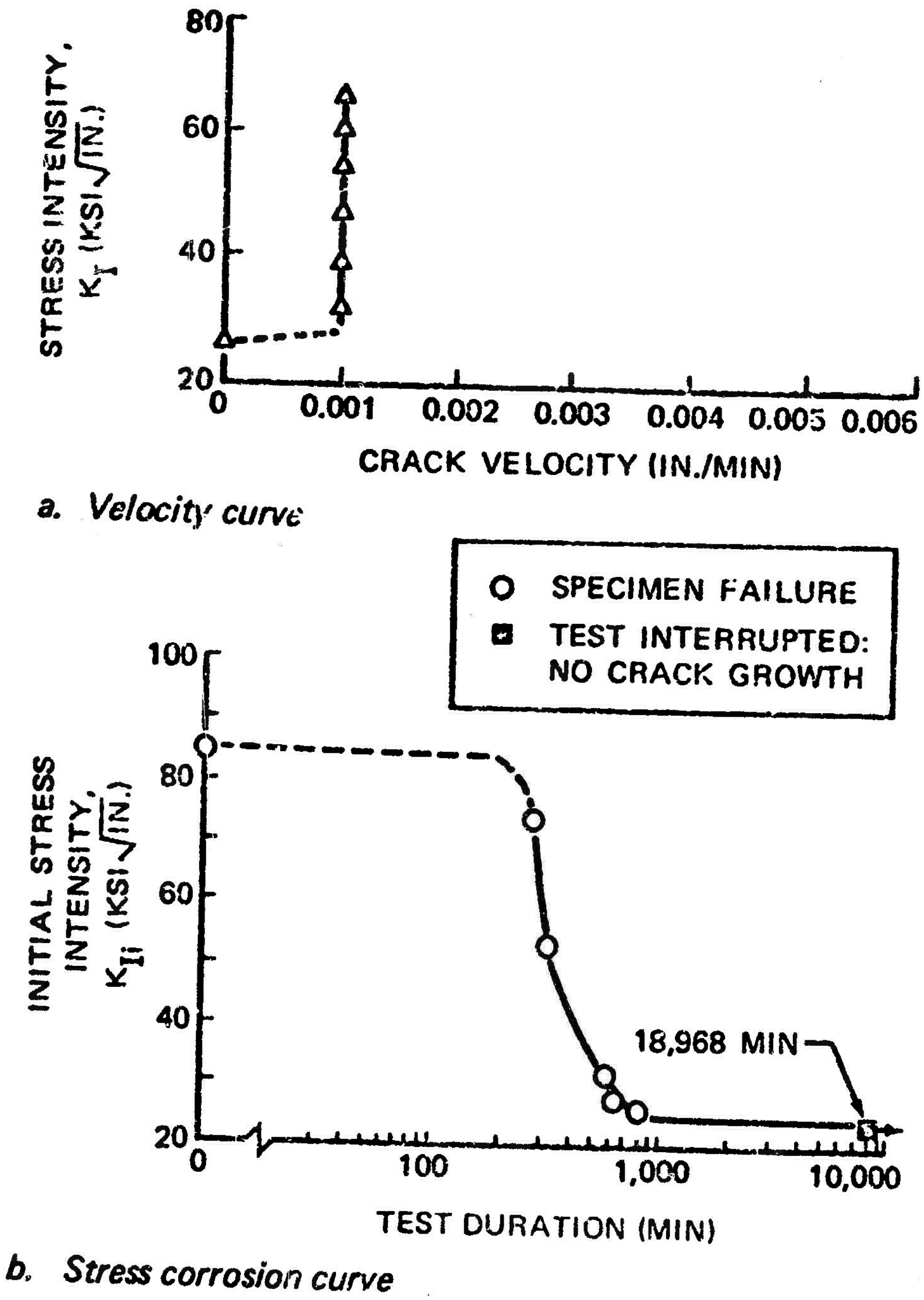


FIGURE 15. Comparison of Stress Corrosion and Crack Velocity Curves for 4340 Steel (1.08% Si), Q&T 800°F.

Source: Carter, 1969.

relationship between cracking velocity and stress intensity exists. This behavior is illustrated in Figure 14-a, while Figure 14-b shows the appearance of the result K versus failure time curve. The versus velocity curve also may show a region in which the growth rate is constant, as illustrated in Figure 15.

From a long time structural reliability standpoint, K_{Iscc} may be more important than the growth rate. Figure 16 shows failure time curves for a variety of steels having an ultimate tensile strength in the range of 234-244 ksi. Although material composition had a significant influence on the kinetics of the stress-corrosion process, the K_{Iscc} parameter essentially was unaffected by variations in steel type (Steigerwald, 1969). In steels with lower strength properties (170 to 195 ksi), manganese and carbon reduce K_{Iscc} while chromium, molybdenum, nickel, and cobalt had no significant effect (Brown, 1970). The susceptibility of a given steel to stress corrosion, measured by either a lowering of K_{Iscc} or an increase in crack growth rate, tends to increase as the strength level is raised.

Studies of the influence of environment on stress-corrosion behavior indicate the following:

- Water vapor in an inert gaseous environment or dry hydrogen gas can produce stress corrosion (Johnson, 1971).
- Variations in solution pH do not produce a marked effect on the environmentally-induced crack growth rate (Vander Sluys, 1966).
- Stress-corrosion type failures occur in high-strength steel in organic environment. The failure time increases as the solubility of the water in the environment increases (Steigerwald, 1960; Rostoker, 1965).

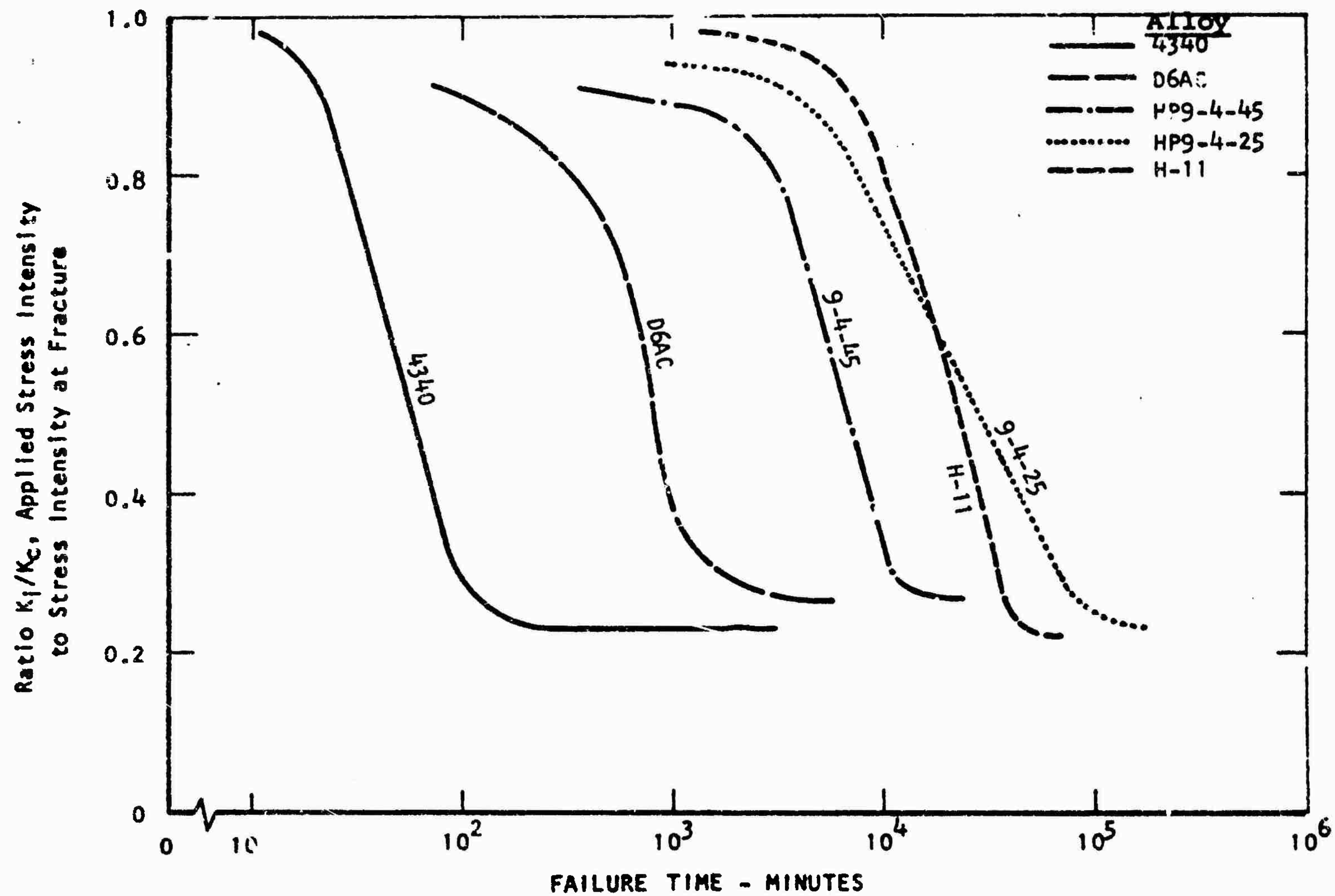


FIGURE 16. Composite Graph of K_i/K_c Ratio Versus Failure Time for Six Martensitic High-Strength Steels, Distilled Water Environment.

Source: Miller, 1961.

- Increasing temperature accelerates the crack-growth rate in a liquid environment and can either retard or accelerate stress corrosion in a gaseous environment (Brown, 1970; Hanna, et al., 1964).
- In high-strength steels, the stress-corrosion process has been attributed to a hydrogen embrittlement mechanism (Brown, 1970; Hanna, et al., 1964; Hancock and Johnson, 1966).

In addition to the delayed failure from external environments, subcritical crack growth also can be produced by hydrogen introduced into steel and titanium alloys during processing, e.g., cleaning and plating (Troiano, 1960). Although the phenomenological characteristics of this type of embrittlement in high-strength steels are similar to stress corrosion, usually, the problem can be handled by proper fabrication controls.

In general, there are many phenomonological aspects of the stress-corrosion process in high-strength titanium and aluminum alloys. Data relating the K_{Iscc} value to the basic fracture toughness (K_{Ic}) of a number of titanium alloys are shown in Figure 17. As in the case of steel, microstructure, strength level, and type of environment can have a significant effect on the stress-corrosion process.

The characteristic crack-growth behavior of a series of aluminum alloys is summarized in Figure 18. Recent work has indicated that a true K_{Iscc} level may not exist for these materials at least in a salt water environment (Brown, 1970). The cracking rate decreases to very low levels with decreasing K but does not completely reach zero.

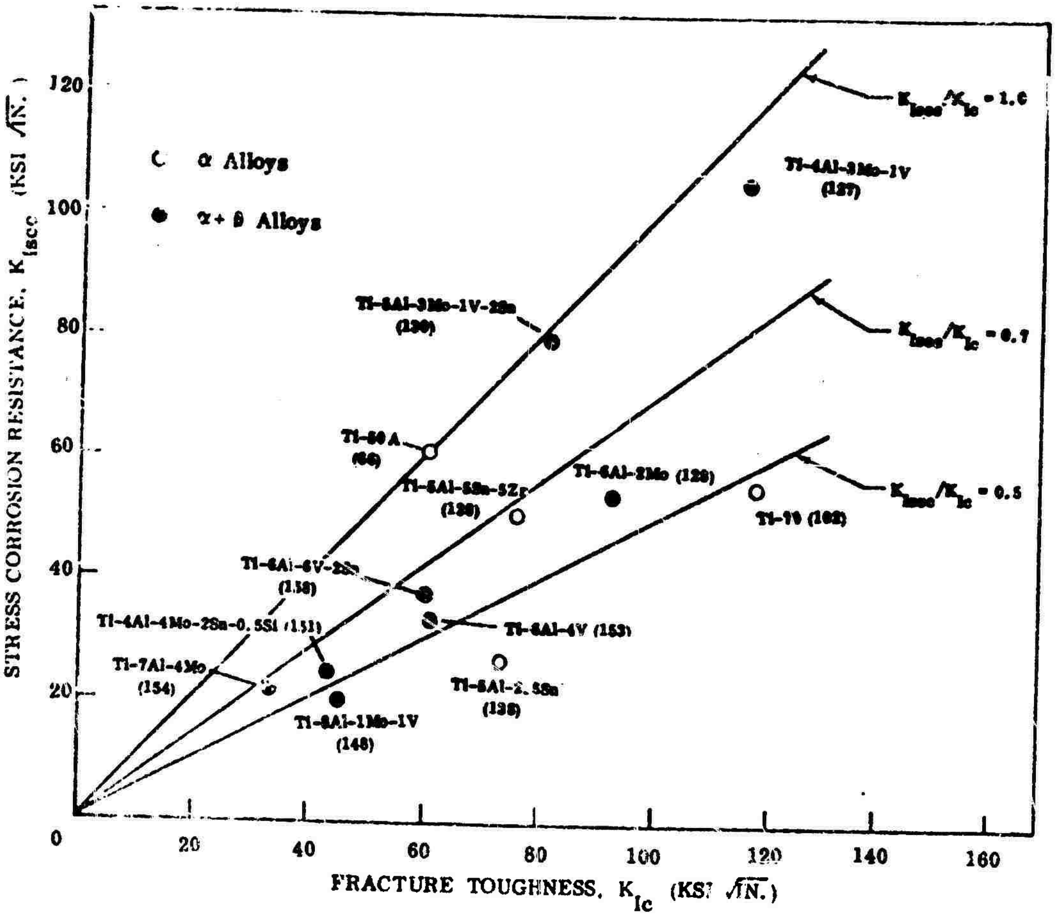


FIGURE 17. Mill Annealed Properties of α and α + β Titanium Alloys. Ultimate tensile strength in ksi is shown in parentheses.

Source: Curtis et al., 1967.

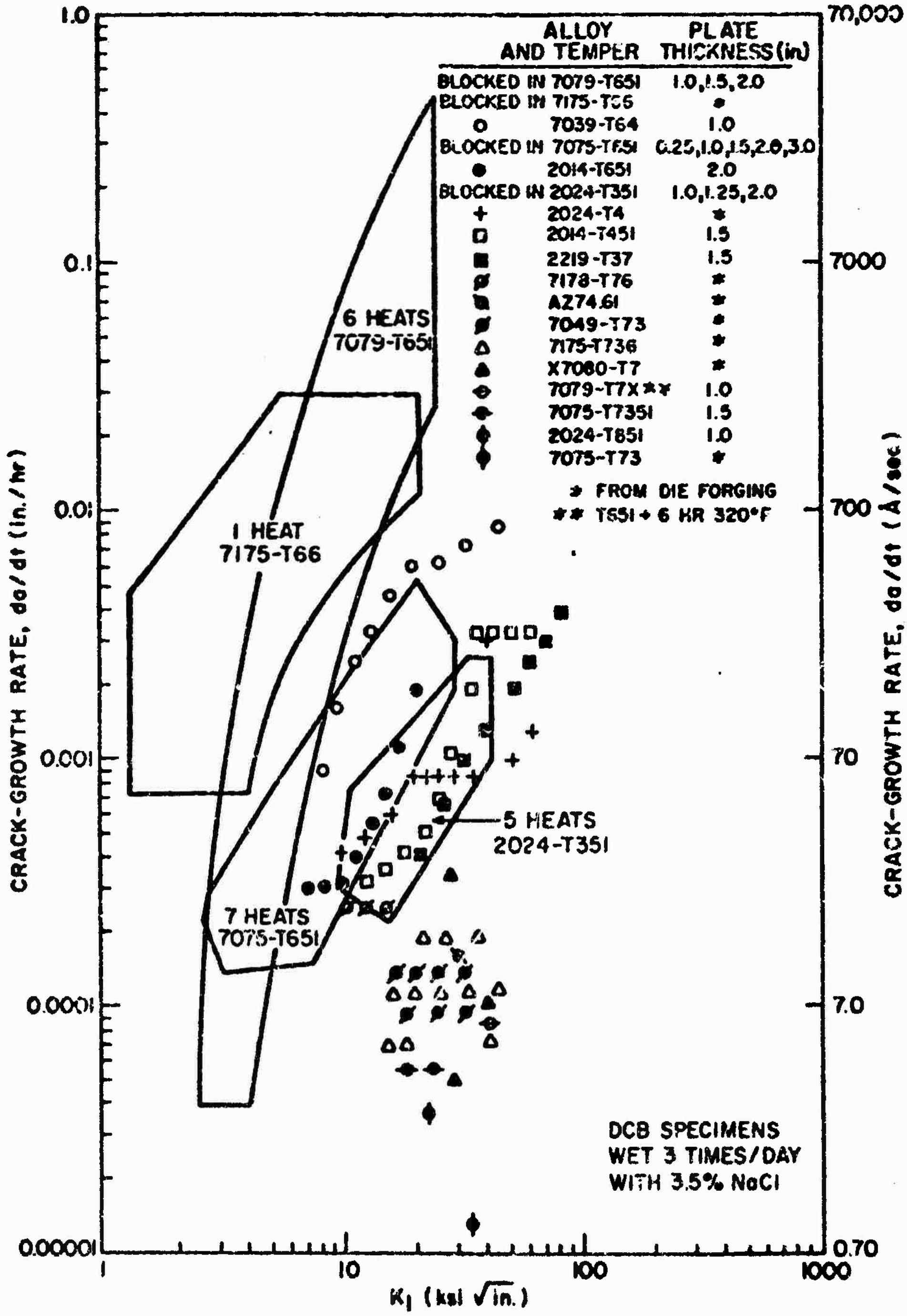


FIGURE 18. Comparison of Several Commercial and Experimental Aluminum Alloys Using the Self-Stressed DCB Specimen and the Crack-Growth Rate Method.

Source: Brown, 1970.

3. Test Methods for Fatigue and Stress-Corrosion Crack Growth

The measurement of subcritical crack growth involves a precracked specimen and a method of determining the degree of crack extension as a function of either test time or number of cycles. Investigators have employed the same methods that are used to measure fracture-toughness properties (see ASTM STP 381 and STP 410 for more details) including: (1) center-notched panels, (2) single-edge notched panels, (3) bend specimens, and (4) surface-cracked specimens. A detailed description of monitoring techniques has been presented in ASTM STP 381 and a brief summary of the types of methods is given in Table 5. In certain cases, the application of an environment eliminates specific monitoring techniques from consideration. More recently, the single-notched precracked (SEN) specimen, loaded as a double cantilever beam, has been used most widely to measure slow crack-growth behavior. This specimen type is economical of material and provides a test condition in which small changes in crack-growth extension can be measured accurately as changes in specimen compliance. No standardized thickness requirements have been defined for slow crack-growth testing and the general requirement is to use specimen thicknesses that are equal to the component geometry.

Fatigue Crack Growth. In the case of cyclic crack growth, standardized test methods such as standardized cyclic frequencies, stress ratios, load spectra, and environments are needed sorely. Information on the reproducibility and the dispersion of growth measurements also must be obtained. Activities, such as the ASTM E-24 round robin on fatigue-crack growth measurement, currently in progress, are a step in this direction and need to be supported.

TABLE 5. Summary of Crack-Monitoring Methods.

Method	Description	Comment
Visual Observation	Direct measurement of crack with travel-microscope.	Simple, may be difficult to apply to stress corrosion.
Cinematography	Motion picture recording of surface-crack extension.	Permanent record, relatively simple difficult to apply to stress corrosion.
Electric Potential	Measurement of potential change as crack extends.	Sensitive, automatic recording, adaptable to stress corrosion and fatigue.
Displacement Gauges	Measurement of specimen compliance change as crack extends.	Relatively sensitive, automatic recording, adaptable to stress corrosion and fatigue, uses common test laboratory equipment.
Acoustic Emission	Measurement of sound emission as crack propagates.	Adaptable to stress corrosion or fatigue, involves special equipment and interpretation.

Source:

Stress-Corrosion Crack Growth. The lack of standardized measurements of stress-corrosion growth is confounding the interpretation of test results and is an obstacle to progress in this field.

At the present time, three types of tests are used to evaluate the crack growth characteristics of metallic alloys in the presence of a corrosive environment:

a. Tests in which the stress intensity increases with crack extension. Examples are the constant load cantilever-bend specimen (Brown, 1966) and a constant load specimen containing a through crack or a surface crack.

b. Constant displacement tests in which the stress intensity decreases with crack extension. An example is the bolt-loaded, edge-crack WOL specimen (Novak and Rolfe, 1969).

c. Tests in which the stress intensity remains constant with crack growth. These employ constant load edge-cracked, tapered-beam specimens developed by Ripling (Mostovoy, et al., 1967).

Various designs of face groove are generally used with the edge-cracked specimens in order to keep the crack in the same plane during the course of its growth.

Two kinds of data may be obtained from each of these specimen types, namely, the time to failure as a function of the applied K-level and kinetic information relating the crack growth rate, da/dt, to the instantaneous value of K. Tests of types (b) and (c) generally are used for kinetic studies. Various methods are used to measure crack growth including

sensing of crack-mouth displacement, direct observation of the surface traces, and electrical potential measurements. Surface-crack specimens present special problems in determining crack-propagation rates. Some investigators have attempted to deduce the crack length change from measurements of the crack-mouth opening. The procedure, as applied, neglects the change in shape of the crack and the progressively developing influence of the back surface on the measured deflections.

Generally, specimens are provided with fatigue cracks, but in some cases, the cracks are started by loading a machined notch to produce a pop-in crack. Only a small amount of information is available concerning the influence of the method of cracking on the crack growth in the subsequent stress corrosion test (Brown, 1970). A large influence of preloading on K_{Iscc} of fatigue-cracked steel specimens has been reported (Carter, 1969). The apparent K_{Iscc} values increased from 8 to 25 ksi-in$^{1/2}$ when the preload stress intensity was increased from zero to $0.90K_{Ic}$. These results would indicate that high fatigue-cracking stress levels or pop-in cracks could result in elevated values of K_{Iscc}. However, the effect of fatigue-crack stress-intensity level apparently depends on the material. The K_{Iscc} of a titanium alloy has been reported unchanged when the fatigue-cracking stress-intensity level was varied from 0.15 K_{Ic} to 0.85 K_{Ic} (Smith and Piper, 1970). Fatigue cracks produced in the corrosive environment could lead to different results in subsequent corrosion tests than fatigue cracks produced in air. No data seem available on this question. However, the effects might be dependent on the material. Generally, specimens are loaded in the presence of the aggressive environment. If the load is applied first, the crack surfaces may passivate and

crack growth will be delayed. Again, the effect will depend upon the material.

Results from increasing K-level constant load tests may give a false impression of material behavior under certain circumstances. In these tests, failure time is plotted as a function of the initial applied K level. Two regions of behavior are observed. At high K levels, the time to failure is not strongly dependent upon the magnitude of the applied stress intensity and, in this region, the process is dominated by transient and unstable crack propagation. With decreasing applied K, the time to failure becomes highly dependent on the stress-intensity level, and there appears to be a K-value (K_{Iscc}) below which no failure will occur. In general, the tests are terminated at some "cutoff" time which is presumably sufficient to establish K_{Iscc}. Unfortunately, this type of test is complicated by very long incubation times that characterize the behavior at low K levels. Thus, if one waits long enough, crack growth will start again and the apparent K_{Iscc} will decrease with increasing cutoff times. This effect has been demonstrated by test results that show the apparent K_{Iscc} for a high-strength steel decreased from 170 ksi-in$^{1/2}$ to 25 ksi-in$^{1/2}$ when the cutoff time was increased from 100 to 10,000 hours (Novak and Rolfe, 1969). Another complicating factor in this type of test is the dependence of failure time on specimen size. Thus, for a given initial applied K-level, the failure time will increase as the length of uncracked ligament increases. This effect is shown by the data generated on a BISRA "round robin" testing program that employed specimens of different sizes (Priest and McIntyre, 1971).

Generally, little attention has been given to the specimen size requirements in K_{Iscc} testing. Accordingly, it is frequently impossible to make useful comparisons of data from different laboratories.

4. Recommendations

a. Standardization is needed badly in the field of cyclic crack-growth and stress-corrosion crack-growth testing using cracked specimens. This need has been recognized by the members of ASTM Committee E-24 on Fracture Testing of Metallic Materials and by ASTM Committee G-1 on Corrosion, Deterioration, and Degradation of Materials. These committees established a joint Task Group to draft standards or recommended practices for stress-corrosion tests using crack specimens. Because the kinetics of the process are complex and as yet not understood completely, standards development will be an evolutionary process. At present, general agreement is needed on one or two specimens designs and the necessary operational controls for conducting the tests. In the case of cyclic crack growth, standardized test specimens, frequencies, environments, and load spectra must be established. These efforts, which require the participation of many laboratories, are hampered greatly by the lack of funds to carry out experiments. Even the relatively modest sums, needed to cover travel expenses to Task Group meetings, are hard to find.

b. The mechanisms of cyclic crack growth, and particularly of corrosion fatigue, require additional study with a view toward reducing the reliance on empirical testing. In the case of fatigue-crack growth, efforts should be made to develop an understanding of the elastic-plastic stress-strain distribution in

Constant displacement tests furnish a K-value at crack arrest which sometimes is reported as K_{Iscc}. If the specimen is designed properly, this value should be independent of the plane dimensions, because the crack length at arrest can be measured directly. However, the effect of long incubation times should be considered in light of a choice of cutoff time. Only a small amount of experience has been gained from using this type of specimen in determining K_{Iscc} values. Some results indicate that the K_{Iscc} from this type of test will depend on the starting K-level, if crack blunting is caused by the environment (Priest and McIntyre, 1971). Thus, if the initial K-level is relatively high, the crack will grow more and blunt more than if the initial K-level was relatively low. For this reason, the K_{Iscc} values can increase with the applied initial K-level.

Constant-K tests often are used to obtain crack-growth rate data. The kinetic information, derived from such tests, can be used to estimate the lives of structural components. However, the translation of test results to service life is complicated by the presence of the incubation period and the nonsteady state phases of crack growth, both of which are a function of the K-level and normally are not considered in the analysis.

Certain requirements are common to all three types of tests. The "in plane" dimensions of the specimen (including the uncracked ligament) must be sufficient that linear elastic mechanics can be applied and, strictly speaking, the thickness must be sufficient to maintain plane-strain conditions if the result is to be characterized by K_I. If face grooves are used to keep the crack in plane, tests must demonstrate that these grooves do not appreciably influence the stress-intensity calibration.

the vicinity of the crack tip and the contribution of the cyclic flow properties that underly crack closure and spectrum loading effects. In the case of corrosion cracking, a better understanding should be developed of the chemistry of the corrosion process as influenced by factors, such as passivation of the crack faces, tightness of the crack, and application of protective measures. Without a better understanding of chemistry now available, it will be difficult to relate laboratory data to service applications.

c. The material, chemical, and geometrical factors that control incubation and growth in the vicinity of K_{Iscc} should be investigated. Recent work has indicated that extremely long incubation times (~10^4 min.) often are required to initiate slow crack-growth in the vicinity of K_{Iscc}. The reason for this effect and its implications for fracture control must be defined. The relation between incubation and growth at low K-levels and corrosion fatigue should be examined to develop correlations between these processes. In addition, an understanding of the geometric and material effects that produce the extended incubation time may lead to the development of materials with improved stress-corrosion resistance.

d. Spectrum-loading effects are also extremely important and a need exists to develop correlations that will allow translation of laboratory or simulated service data to actual component performance, with a minimum of testing.

e. Regression parameters for stress corrosion and cyclic crack-growth measurements in different materials should be established. A round robin, organized by ASTM E-24, currently is collecting regression parameters for cyclic crack-growth measurements, but this should be regarded only as a useful first step.

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APPENDIX D

NONDESTRUCTIVE EVALUATION

CONTENTS

NONDESTRUCTIVE EVALUATION

1. NDE Requirements

The increased use of high-performance materials in aircraft airframe and engine components requires more thorough application of NDE techniques at all stages of hardware flow from the acceptance of raw materials to inflight inspection of critical components. With the advent of new materials and design concepts and because of the criticality of smaller defects, we become increasingly dependent on improving our NDE capabilities to prevent structural failures such as those that have attended the flight operation of a number of airframes and engine components. Moreover, each stage in the development and application of materials should be integrated with NDE requirements. As indicated in the attached chart, Figure 19, each stage of hardware flow should be coordinated with its NDE counterpart to insure that appropriate, sensitive methods are available during each step in hardware processing, assembly, and operation.

2. Material Acceptance and Processing

Undoubtedly, many structural failures in service may be attributed to imperfect control of material quality, e.g., introduction of impurities, improper heat treatment, and strain hardening. Generally, metals and alloys are not entirely uniform in composition or density. Therefore, nondestructive inspection and evaluation techniques are needed to insure that the most homogeneous and cleanest possible materials enter the forming and finishing stages. The application of NDE techniques should begin when structural materials are in their primal stage, for example, slabs or billets, which may contain porosity, voids,

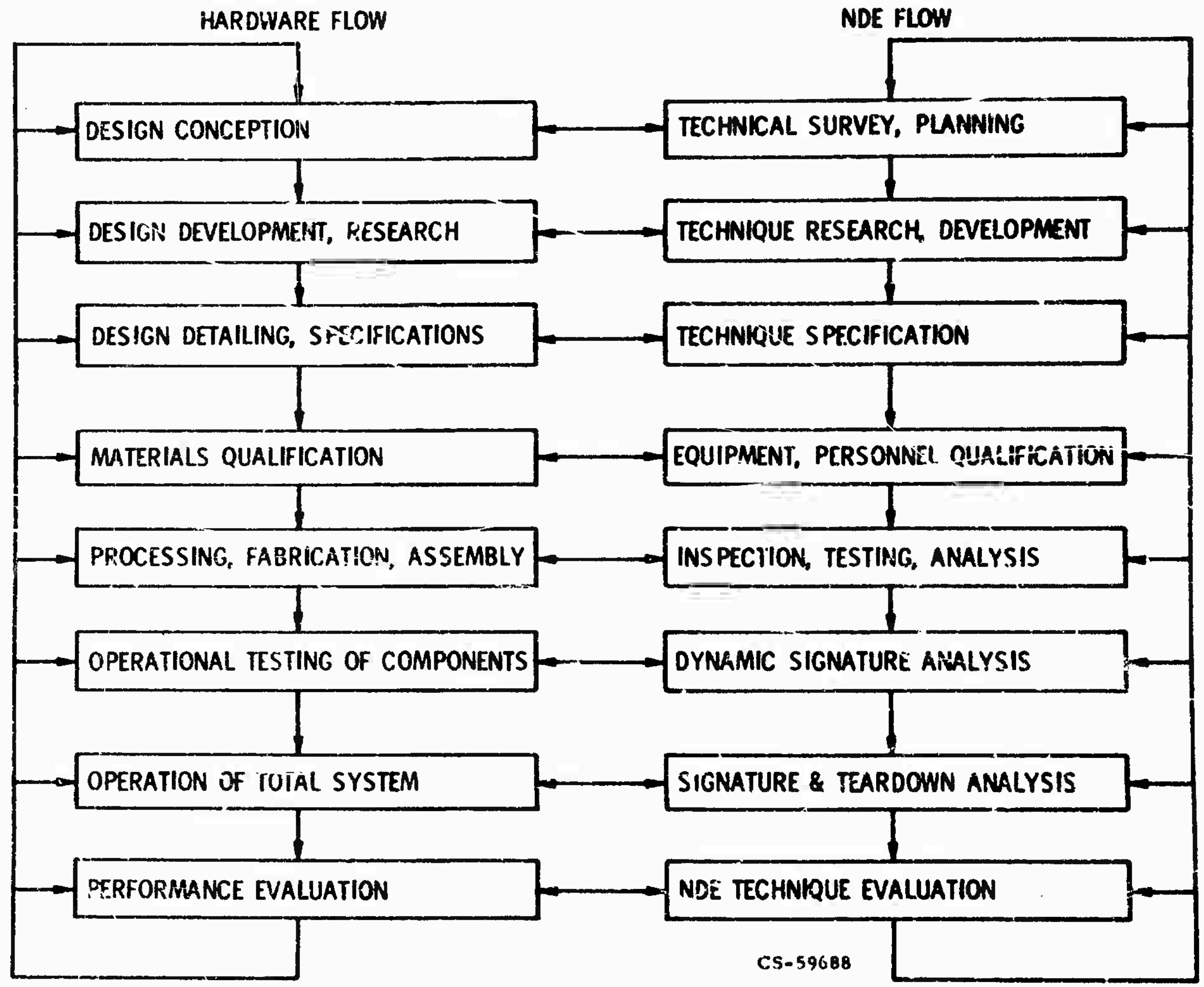


FIGURE 19. Relation of NDE and Hardware Flow.

Source: A. M. Vary, NASA-Lewis Research Center, 1972.

segregations, impurities, and particulate inclusions. When applied at this early stage, NDE techniques could lead to improved melting practices and result in improved properties of any alloy. The mechanical working of an ingot, i.e., forming, rolling, or extrusion, tends to introduce residual stresses, scales, laminations, and other mechanical flaws. Generally, the processing of raw materials, casting, hot- and cold-working tend to produce cracks because of a variety of imperfections introduced at earlier stages. Therefore, good practice, requires inspection of raw materials either before or when they enter the production facility. This inspection can be assigned to the materials supplier, an independent test facility, or to a receiving inspection testing department at the production facility.

The techniques applied to raw materials should include in-process inspection during various forming operations. It is equally important to apply NDE methods during the intermediate finishing, machining, welding, and similar processing stages when access to the part is most readily available. Careful attention should be given to processing steps and treatments that may introduce defects which become hidden and difficult to detect after further fabrication. The objectives of NDE of raw materials and partially completed parts are to determine items such as dimensional variations, roughness, laminations, inclusions, porosity, cracks, micro- and macro-discontinuities, alloy identification, hardness, grain size, and stress.

3. <u>Inspection of Finished Parts</u>

Often the only time a material, part, or component can be inspected reasonably is when it has been processed completely. At this stage, considerable effort and ingenuity may be required to perform adequate examinations for flaws because of factors such as shape and size, contours, thickness variations, convolutions, and inaccessible zones. Thus, geometry, surface roughness, and metallurgical structure and state can conspire against adequate inspection. Accordingly, there will be a considerable variation in defect-detection capability, and adequate inspection will depend upon knowledge of interfering effects and of experience and innovation in the application of NDE techniques. To a larger extent, these problems can be minimized if the test conditions and evaluation criteria can be established precisely and repeated. This stage is particularly critical since finished parts, fashioned from higher strength materials, tend to be less tolerant of smaller flaws. Typically, these materials have relatively low fracture values so that very small discontinuities can lead to catastrophic failures. At this stage, full-size parts, containing actual and artificial defects, may be required to serve as standards against which NDE methods may be calibrated. In many cases, the variables and small defect dimensions require the use of programmed machine operation of probes and electronic data processing. NDE of finished parts include objectives, such as metrology, surface condition, process residues, discontinuities (e.g., cracks, disbonds), residual stress, and metallurgical condition.

4. Inspection of Fabricated Assemblies

Presumably, finished parts used in assembling structures and components have met evaluation critera, as certified by prior inspections. However, subsequent inspections will be required not only to assess the flightworthiness of the total assembly but also to determine whether new flaws were introduced into the previously examined parts. For example, the attachment of wing panels to the airframe may introduce cracks or stresses, especially in areas near fasteners. The NDE of fabricated assemblies is complicated by the fact that defective zones may become inaccessible. At this stage, the designer should introduce devices and features that enhance the inspectability of the assembly. For critical components, the concept of built-in inspectability may be the most vital aspect of design considerations. Proper integration sensors and signal generators will depend on preliminary testing of components and the testing of communication channels available in the assembled structure, e.g., paths for effective transmission of acoustic signals and pinpointing of defect loci.

5. In-Situ Inspection

The final and most challenging problems arise in the inspection and evaluation of critical components of a finished aircraft at various times during its service life. Inspection and, sometimes, testing during maintenance intervals are involved. Critical components, as determined during test and service experience, may require more frequent inspections. Of course, the frequency and sensitivity of inspections will depend on the length of the smallest crack that must be detected to prevent failure. Identification of critical components or

zones is a vital prerequisite but only a preliminary factor in NDE. With many types of aircraft, economic and practical constraints demand that these components be inspected with little or no disassembling of the vehicle. Thus, a great deal of ingenuity and preparation is required to search for and evaluate flaws, such as cracks around fastener holes, corrosion under a fuselage skin lap, and compressor hub and blade root cracks. One of the reasons for examining service aircraft for flaws is that inflight conditions (e.g., temperature, pressure, humidity) will differ drastically from those encountered during ground tests.

Among the <u>in situ</u> diagnostic methods that may be of value in fracture detection and monitoring on a flight or ground test aircraft are a group of techniques broadly categorized under "signature analysis." Signature analysis may be defined as any NDE technique that senses characteristic signals (acoustic emission, ultrasonic spectroscopy, etc.) spontaneously generated by crack extension and uses these signals to determine levels of structural damage. At present, these methods are in an embryonic state of development regarding application to a complete aircraft.

6. Current Methods of NDE

For many inspection tasks connected with hardware stages ranging from raw materials through finished vehicles, a number of conventional techniques should form the basis of any fracture-control program. These techniques are visual-optical, liquid penetrant, magnetic particle, sonic-ultrasonic, eddy current, and X- and gamma-ray film radiography. During the initial material-processing stages, of course, these techniques

can be applied readily and directly to characterize materials and to determine whether they meet specifications. So long as uncomplicated parts are involved, the aforementioned and other methods in current use can be applied to eliminate defective materials and parts from further processing and fabrication stages. Thus, a number of conventional techniques are available to evaluate hardware items with respect to discontinuities, inclusions, voids, inhomogeneities, dimensions, and some physical and mechanical properties. Although seemingly simple, these techniques often are applied improperly. Brief resumés of these NDE methods follow. (General guidelines for conventional NDE techniques are given in Fig. 20.)

a. Surface Flaws

Visual, mechano-optically-aided examinations generally are valuable for checking surfaces for flaws, irregularities, and dimensional characteristics. Optical metrology, involving various phenomena of light optics, always should be given consideration in any NDE procedure. Visual methods should be used as separate inspection tools and to provide information prior to performing other NDE checks. Although visual methods are limited to items with accessible surfaces, fiber-optic devices can extend greatly the range of visual examination into fairly tortuous and confined regions.

Liquid-dye or fluorescent penetrants can be used on virtually any material, provided it is nonabsorbent and the flaws are surface connected. The part geometry is relatively unimportant but the surface must be accessible and clean. In penetrant inspection, it is necessary, first, to remove all surface contaminants and, after inspection, to remove the

Figure 20.

Nondestructive Testing Methods for Materials Evaluation

Compiled by D. J. Hagemaier, Douglas Aircraft Company

	SONIC	ACOUSTIC-IMPACT (Tapping)	ACOUSTIC EMISSION	PENETRANTS	MAGNETIC PARTICLES	ELECTRIFIED PARTICLE
MEASURES OR DETECTS	1. Debonded areas or delaminations in metal or non-metal composites or laminates 2. Cohesive bond strength under controlled conditions 3. Crushed or fractured core 4. Bond integrity of metal insert fasteners	1. Debonded areas or delaminations in metal or non-metal composite or laminates 2. Cracks under bolt or fastener heads 3. Cracks in turbine wheels or turbine blades 4. Loose rivets or fastner heads 5. Crushed core	1. Crack initiation and growth rate 2. Internal cracking in welds during cooling 3. Boiling or cavitation 4. Friction or wear	Defects open to surface of parts; cracks, porosity, etc	Surface and slightly subsurface defects; cracks, seams, porosity, inclusions	1. Surface defects in nonconducting materials 2. Through-to-metal pinholes on metal-backed material 3. Tension, compression, cyclic cracks 4. Brittle-coating stress cracks
APPLICATIONS	1. Metal or non-metal composite or laminates brazed or adhesive-bonded 2. Plywood 3. Honeycomb 4. Rocket motors	1. Brazed or adhesive-bonded structures 2. Bolted or riveted assemblies 3. Turbine blades 4. Turbine wheels	1. Pressure vessels 2. Stressed structures 3. Turbines or gear boxes 4. Fracture mechanics research	All parts with non-absorbing surfaces Note: Bleedout from porous surfaces can mask indications of defects	Ferromagnetic materials; bar, forgings, weldments, extrusions	1. Glass 2. Porcelain enamel 3. Non-homogenous materials such as plastic or asphalt coatings 4. Glass-to-metal seals
ADVANTAGES	1. Portable 2. Easy to operate 3. Locates far-side debonded areas 4. May be automated 5. Access to only one surface required	1. Portable 2. Easy to operate 3. May be automated 4. Permanent record or positive meter readout 5. No couplant required	1. Remote and continuous surveillance 2. Permanent record 3. Dynamic rather than static detection of cracks 4. Portable	1. Low cost 2. Portable 3. Indications may be further examined visually 4. Results easily interpreted	1. Advantage over penetrant in that it indicates sub-surface defects; particularly inclusions 2. Relatively fast and low cost 3. May be portable	1. Portable 2. Useful on materials not practical for penetrant inspection
LIMITATIONS	1. Surface geometry influences test results 2. Reference standards required 3. Adhesive or core thickness variations	1. Part geometry and mass influences test results 2. Impactor and probe must be repositioned to fit geometry of part 3. Reference standards required	1. Transducers must be placed on part surface 2. Highly ductile materials yield low amplitude emissions 3. Part must be stressed or operating	1. Surface films, such as coatings, scale, and smeared metal may prevent detection of defects 2. Parts must be cleaned after inspection	1. Alignment of magnetic field may be difficult in some complex shapes 2. Demagnetization of parts required after tests 3. Parts must be cleaned after inspection 4. Thick surface coatings	1. Poor resolution on thin coatings 2. False indications from moisture streaks or lint 3. Atmospheric conditions 4. High voltage discharge

	RADIOGRAPHY (Gamma Rays)	RADIOGRAPHY (X-Rays) (Film and Fluoroscopy)	RADIOGRAPHY (Thermal Neutron)	RADIOMETRY (X-Ray, Gamma-Ray Beta-Ray)	ULTRASONIC	EDDY-SONIC
MEASURES OR DETECTS	Internal defects and variations; porosity inclusion, cracks, lack of fusion, geometry variations, corrosion	Internal defects and variations, porosity, inclusion, cracks, lack of fusion, geometry variations, corrosion	1. Hydrogen contamination of titanium or zirconium alloys 2. Defective or improperly loaded pyrotechnic devices 3. Improper assembly of metal, non-metal parts	1. Wall thickness 2. Plating thickness 3. Variations in density or composition 4. Fill level in cans or containers 5. Inclusions or voids	1. Internal defects and variations, cracks, lack of fusion, porosity, inclusion, delaminations, lack of bond 2. Thickness or velocity	1. Debonded areas in metal-core or metal-faced honeycomb structures 2. Delaminations in metal laminates or composites 3. Crushed core
APPLICATIONS	Usually where X-ray machines are not suitable because source cannot be placed in parts with small openings and/or power source not available	1. Castings 2. Electrical assemblies 3. Welds 4. Small, thin, complex wrought products 5. Nonmetallics	1. Pyrotechnic devices 2. Metallic, non-metallic assemblies 3. Biological specimens	1. Sheet, plate, strip, tubing 2. Nuclear reactor fuel rods 3. Cans or containers 4. Plated parts	1. Wrought metals 2. Welds 3. Brazed joints 4. Adhesive-bonded joints 5. Nonmetallics 6. In-service parts	1. Metal-core honeycomb 2. Metal-faced honeycomb 3. Conductive laminates such as boron or graphite fiber composites 4. Bonded metal panels
ADVANTAGES	1. Low initial cost 2. Permanent records; film 3. Small sources can be placed in parts with small openings 4. Portable	1. Permanent records; film 2. Adjustable energy levels 3. High sensitivity to density changes 4. No couplant required 5. Geometry variations do not effect direction of X-ray beam	1. High neutron absorption by hydrogen, boron, lithium, cadmium 2. Low neutron absorption by most metals 3. Compliment to X-ray or gamma-ray radiography	1. Fully automatic 2. Fast 3. Extremely accurate 4. In-line process control 5. Portable	1. Most sensitive to cracks 2. Test results known immediately 3. Automating and permanent record capability 4. Portable 5. High penetration capability	1. Portable 2. Simple to operate 3. No couplant required 4. Locates far-side debonded areas 5. Access to only one surface required 6. May be automated
LIMITATIONS	1. One energy level per source 2. Source decay 3. Radiation hazard 4. Trained operators 5. Lower image resolution 6. Cost related to energy range	1. High initial costs 2. Orientation of linear defects in part may not be favorable 3. Radiation hazard 4. Depth of defect not indicated 5. Sensitivity decreases with increase in thickness of part	1. Very costly equipment 2. Nuclear reactor required 3. Trained physicists required 4. Radiation hazard 5. Non-portable 6. Indium or gadolinium screens required	1. Radiation hazard 2. Beta-ray useful for ultra-thin coatings only 3. Source decay 4. Reference standards required	1. Couplant required 2. Small, thin, complex parts may be difficult 3. Reference standards required 4. Trained operators for manual inspection	1. Specimen or part must contain conductive materials to establish eddy-current field 2. Reference standards required

Source: Materials Evaluation, Vol. XXVIII, No. 6, June 1970, pp. 25A-28A.

	FILTERED PARTICLE	EDDY CURRENT	ELECTRIC CURRENT	MAGNETIC FIELD	THERMOELECTRIC	DIELECTRIC
MEASURES OR DETECTS	1. Cracks 2. Porosity 3. Differential absorption	1. Surface and sub-surface cracks and seams 2. Alloy 3. Heat treatment 4. Wall thickness, coating thickness, crack depth	1. Cracks 2. Crack depth 3. Resistivity 4. Wall thickness 5. Corrosion induced wall-thinning	1. Cracks 2. Wall thickness 3. Hardness 4. Coercive force 5. Magnetic anisotropy 6. Magnetic field 7. Non-magnetic coating thickness on steel	1. Thermoelectric potential 2. Coating thickness 3. Physical properties	1. Dielectric constant 2. Dissipation factor 3. Degree of cure 4. Moisture detection 5. Thickness
APPLICATIONS	1. Porous materials such as clay, carbon, powdered metals, concrete 2. Grinding wheels 3. High-tension insulators 4. Sanitary ware	1. Tubing 2. Wire 3. Ball bearings 4. "Spot checks" on all types of surfaces	1. Metallic materials 2. Electrically conductive materials 3. Train rails	1. Ferromagnetic materials 2. Ship degaussing 3. Liquid level control 4. Treasure hunting 5. Wall thickness of non-metallic materials 6. Material sorting	1. Metal sorting 2. Ceramic coated metals	1. Phenolic reinforced structures 2. Glass-epoxy structures
ADVANTAGES	1. Colored or fluorescent particles 2. Leaves no residue after baking part over 400°F 3. Quickly and easily applied 4. Portable	1. No special operator skills required 2. High speed, low cost 3. Automation possible for symmetrical parts 4. Permanent record capability for symmetrical parts 5. No couplant or probe contact required	1. Access to only one surface required 2. Battery or d-c source 3. Portable	1. Measurement of magnetic material properties 2. May be automated 3. Easily detects magnetic objects in non-magnetic material 4. Portable	1. Portable 2. Simple to operate 3. Access to only one surface required	1. Portable 2. Access to only one surface required
LIMITATIONS	1. Size and shape of particles must be selected before use 2. Penetrating power of suspension medium is critical 3. Particle concentration must be controlled 4. Skin irritation	1. Conductive materials 2. Depth of penetration; thin walls only 3. Masked or false indications caused by sensitivity to variations, such as part geometry 4. Reference standards required	1. Edge-effect 2. Surface contamination 3. Good surface contact required 4. Difficult to automate 5. Electrode spacing 6. Reference standards required	1. Permeability 2. Reference standards required 3. Edge-effect 4. Probe lift-off	1. Hot probe 2. Difficult to automate 3. Reference standards required 4. Surface contaminants 5. Conductive coatings	1. Probe geometry 2. Reference standards required 3. Unwanted or mixed variables

	THERMAL (Thermochromic Paint, Liquid Crystals)	THERMAL OR INFRARED (Radiometers)	MICROWAVE	HOLOGRAPHIC INTERFEROMETRY	NEUTRON ACTIVATION ANALYSIS	LEAK TESTING
MEASURES OR DETECTS	1. Lack of bond 2. Hot spots 3. Heat transfer 4. Isotherms	1. Lack of bond 2. Hot spots 3. Heat transfer 4. Isotherms	1. Cracks, holes, debonds etc in non-metallic parts 2. Changes in composition, degree of cure, moisture content 3. Highly accurate measurement of thickness and position	1. Stress and strain 2. Plastic deformation 3. Cracks 4. Debonds 5. Voids and inclusions 6. Vibration	1. Radiation emission resulting from neutron activation 2. Oxygen in steel 3. Nitrogen in food products 4. Silicon in metals and ores	1. Leaks
APPLICATIONS	1. Brazed joints 2. Adhesive-bonded joints 3. Metallic platings or coatings 4. Electrical assemblies	1. Brazed joints 2. Adhesive-bonded joints 3. Metallic platings or coatings; debonds or thickness 4. Electrical assemblies	1. Reinforced plastics 2. Chemical products 3. Ceramics 4. Resins 5. Rubber 6. Wood 7. Liquids 8. Polyurethane foam 9. Radomes	1. Bonded and composite structures 2. Metals 3. Automotive or aircraft tires	1. Metallurgical 2. Prospecting 3. Well logging 4. Oceanography 5. On-line process control of liquid or solid materials	1. Joints: Welded Brazed Adhesive-bonded 2. Sealed assemblies
ADVANTAGES	1. Very low initial cost 2. Can be readily applied to surfaces which may be difficult to inspect by other methods 3. No special operator skills	1. Sensitive to 1.5°F temperature variation 2. Permanent record or thermal picture 3. Quantitative 4. Remote sensing; need not contact part 5. Portable	1. Between radio waves and infrared in the electromagnetic spectrum 2. Portable 3. Contact with part surface not normally required 4. Can be automated	1. Surface of test object can be uneven 2. No special surface preparation of coatings required 3. No physical contact with the test specimen	1. Automatic systems 2. Accurate (ppm range) 3. Fast 4. No contact with sample 5. Sample preparation minimal	1. High sensitivity to extremely small, tight separations not detectable by other NDT methods 2. Sensitivity related to method selected
LIMITATIONS	1. Thin-walled surfaces only 2. Critical time-temperature relationship 3. Image retentivity effected by humidity 4. Reference standards required	1. Costly equipment 2. Liquid nitrogen cooled detector 3. Critical time-temperature relationship 4. Poor resolution for thick specimens 5. Reference standards required	1. Will not penetrate metals 2. Reference standards required	1. Vibration free environment is required 2. Heavy base to dampen vibrations	1. Radiation hazard 2. Not portable 3. Fast decay time	1. Accessibility to both surfaces of part 2. Smeared metal or contaminants may prevent detection 3. Cost related to sensitivity

Source: Materials Evaluation, Vol XXVIII, No. 6, June 1970, pp 25A-28A.

penetrant materials. Penetrant inspection is used widely to locate cracks on the surface of drawn, forged, and machined parts. Sometimes penetrants can be used for leak checking by examinining the opposite side of relatively thin-walled parts for penetrant bleed-through.

Magnetic particle inspection can be used to detect surface and subsurface discontinuities, inclusions, and segregations. Generally, this technique can be applied only on ferromagnetic materials although it can detect ferromagnetic inclusions in nonferromagnetic materials. Films or thin coatings on the surface will not affect the detectability of flaws greatly. However, complex shapes can cause inspection difficulties. To perform magnetic particle inspection, it is necessary, first, to magnetize the part or area to be inspected and, subsequently, to demagnetize it after inspection.

Eddy-current inspection is useful for locating near-surface discontinuities and inclusions and for discriminating among metals and alloys with different electrical or magnetic properties. This technique is limited to electrically conducting materials although nonmetallic contaminants, films, or coatings do not affect the results significantly. For each application, eddy-current probes must be tailored to accommodate the part geometry that, in some instances, can impose severe limitations on the area over which the technique can be applied meaningfully. However, the technique is capable of inspecting large quantities of material rapidly and can be automated easily. Physical contact between the probe and part is not required. When used for detecting discontinuities or inclusions, the eddy-current display or readout may tend to be confusing due to effects such as variations in air gap, conductivity, or permeability.

b. Interior Flaws

Sonics and ultrasonic inspection can involve a wide variety of methods ranging from tapping or acoustic impact to ultrasonic spectroscopy. For example, sonic vibration testing can reveal structural anomalies and cracks. Ultrasonic techniques can be applied to many kinds of materials. However, they are particularly valuable inspection means for smooth-surfaced, fine-grained metals and alloys. With ultrasonics, fine cracks and other discontinuities and anomalies can be located at a considerable distance beneath the surface. Relatively great thicknesses of material can be tested from any accessible surface, but an acoustic couplant is required between this surface and the ultrasonic transducer. For example, a part can be inspected by coupling with a film of oil or by immersing both the part and transducer in a container of water. Discontinuities and other acoustic interfaces within the part can be detected, located, and often characterized with respect to their size, shape, and orientation. Automation of ultrasonic scanning is common and a permanent record or map of flaws within the part may be obtained. Complex parts and parts with rough surfaces or large-grained materials are sometimes impossible to inspect satisfactorily.

Film radiography (X-ray and gamma-ray) is widely used and respected for detecting interior flaws. The shape and approximate depth of flaws are determined readily in almost any material, provided examined parts or assemblies are not excessively thick, dense, or complex. Often, film radiography is used to check or confirm results of other techniques and in combination with electronic fluoroscopy. Although resolution and contrast are poorer with fluoroscopy, it has the advantage of producing real-time images

of moving items and permits orientation of test items at advantageous viewing angles to reveal flaws. Despite special precautions, needed to overcome radiation hazards, radiography is accomplished readily in the field and at processing sites for on-the-spot inspection.

c. Proof-Load Testing

Loading a structure to stresses, exceeding those expected in service, is known as proof testing. This procedure is not generally practical because of the large ratio of proof to design load that is needed to preclude failure from flaw growth over a long period of service. However, it is discussed here because of its use and value in special cases. Sometimes proof testing may be used to verify a minimum level of static strength, but this has no direct relevance to the fracture-control plan. The applied loads may be either static and/or dynamic. In a fracture-control plan, the word "proof" implies that if the structure does not fail in the proof test, it will not fail by crack-propagation service. In a sense, the proof test may be a part of a comprehensive NDE program. Proof testing has been applied to ground-equipment pressure vessels for many years. However, until recently, there was no rational way of determining the necessary overload to insure safe operation of the vessel. As a consequence, large factors of safety were (and still are) used in determining both the "safe" operating stresses and the proof loads. Of course, this situation is intolerable for aircraft structures.

Fracture mechanics provides a method for rational design of a proof test and the integration of laboratory fracture data into that design. The general principles are illustrated

in Figure 21 which shows a generalized relation between flaw size and failure stress. For a brittle material, the location of this curve below the yield strength can be established by calculations based on the plane-strain fracture toughness, K_{Ic}. For situations where the failure of the component is not expected to be controlled by K_{Ic}-type behavior, the curve shown in Figure 21 can be generated by suitable laboratory tests on specimens containing cracks of different sizes. From this relation and the proof stress, an upper limit is assigned to the flaw size which can exist after proof. The difference between this flaw size and that which corresponds to the maximum operating stress is the margin for flaw growth in service without failure of the structure. For a sufficiently brittle material, this failure may be catastrophic; while for a sufficiently tough material, failure may represent crack penetration through thickness (e.g., a leak in a pressure vessel). Of course, all variations between these extremes are possible, depending on the toughness of the material and the thickness of the part containing the crack.

If failure is defined as penetration of the structure by a crack (e.g., leak in the wall of a pressure vessel), a proof test may not provide assurance against failure during subsequent operation where sufficiently tough materials are involved. Consider a pressure vessel made from a material sufficiently tough that a through-thickness crack, two to three times the wall thickness in length, will be stable at stresses equal to the yield strength. If the proof stress is limited to the yield strength, a situation might occur where a surface flaw would pass proof testing yet be deep enough to result in thickness penetration after a small number of load cycles at the operating stress. Under these circumstances, a proof test may damage the

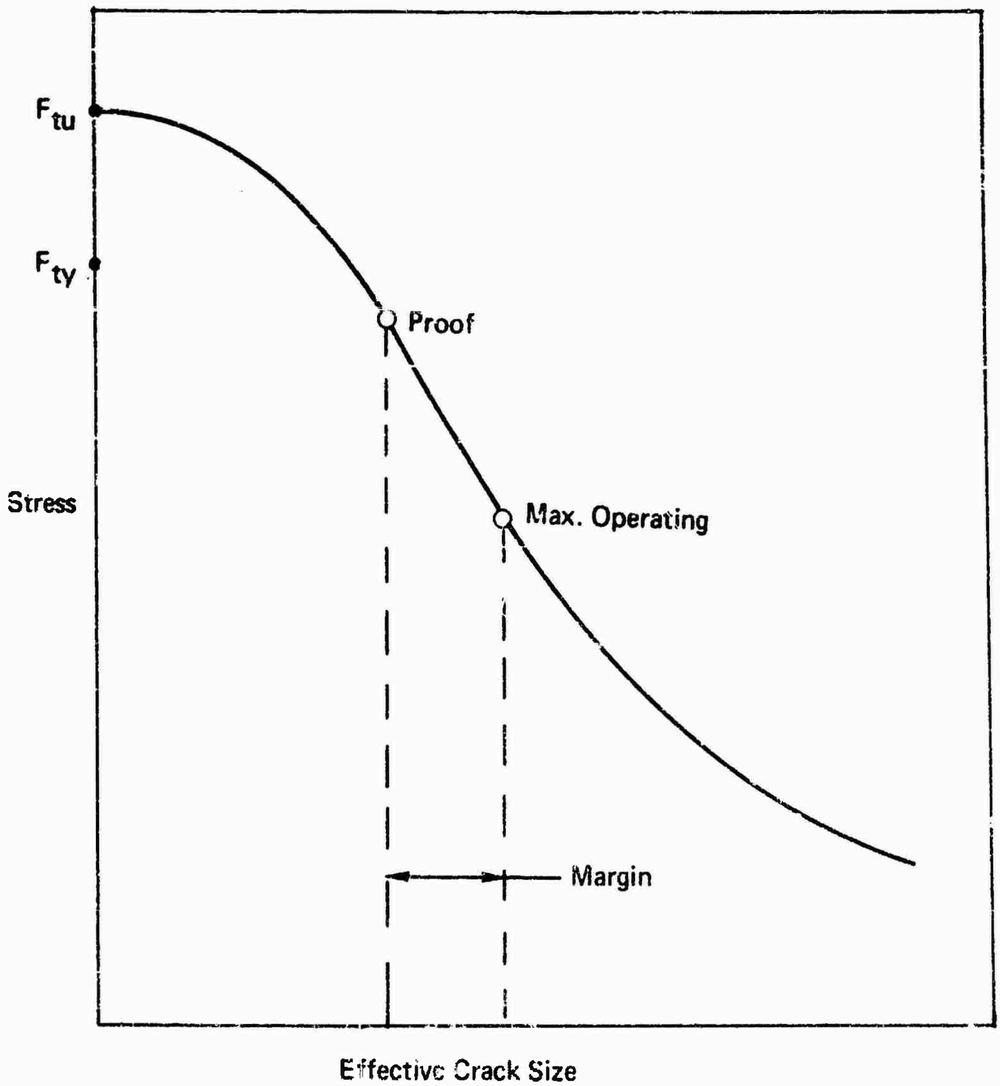


FIGURE 21. Examples of Subcritical Crack Growth.

structure by producing crack extension under the proof load. The safest procedure would be to substitute a leak test at the operating stress for the proof test. It might be argued that extended cyclic life could be obtained by occasional overloads (repeated proofs) due to their retardation effect on crack propagation at lower stress levels. However, this retardation effect may or may not occur depending on the crack size and geometry, neither of which are known. The outlined general procedure involves a number of assumptions, and in many cases, the margin for flaw growth, remaining after proof, is subject to considerable uncertainty. Among these assumptions are:

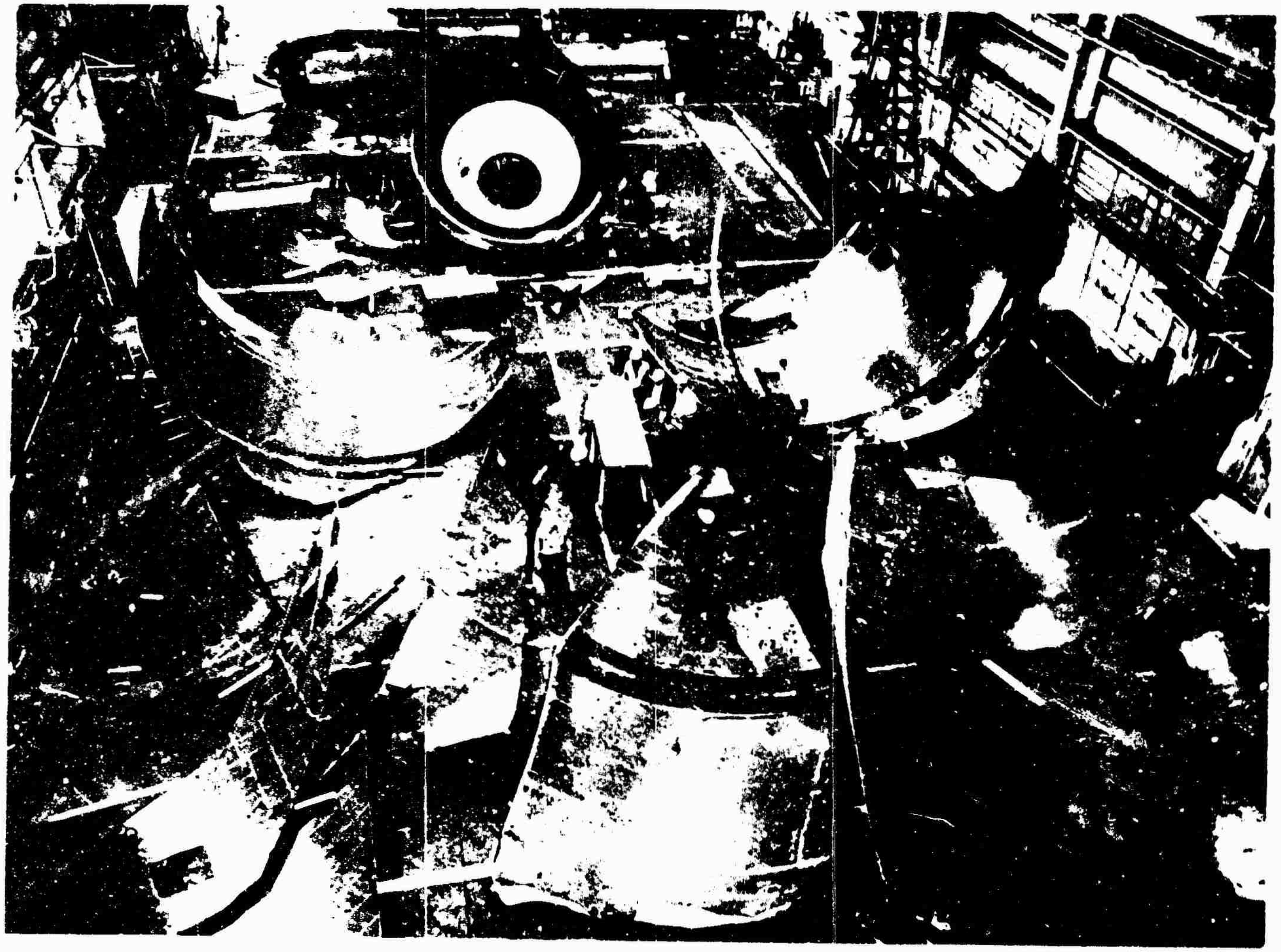
- Operational loads can be simulated properly during proof.
- Sufficient margin exists between maximum operating stress and yield strength to provide an effective proof stress without general yielding of the structure.
- The generalization of crack shape, used to calculate an effective flaw size, will apply equally well to the flaw in the laboratory specimen and that in the structure.
- The important features of the service environments can be reproduced in the laboratory crack-growth studies.
- Account can be taken of features, not incorporated in the laboratory fracture tests, such as the influence of residual stresses and abrupt changes in geometry in the vicinity of the flaw in the structure.

Furthermore, the structure must be designed initially with a proof test in mind, or possibly, some critical portion of the structure cannot be subjected to the proof loads without damaging other portions. Obviously, the uncertainties accompanying the design of a proof test for a homogeneous wall

pressure vessel subject to one operating cycle will be considerably lower than those for military aircraft. However, for complex structures, the reliability of detecting critical cracks through proof test can be increased by making worst possible case assumptions in all steps of the process. In effect, these assumptions increase the difference between the operating stress and the proof stress and represent possible reductions in vehicle performance.

Where used, proof testing may be combined with other NDE procedures. Crack extension under proof loads in some circumstances may be detected by NDE methods providing signature analysis (e.g., acoustic monitoring). In some instances, cracks so located may be repaired. Furthermore, proof loading tends to open cracks and a post-proof inspection may reveal flaws that were not detected previously.

A striking example of how a proof-load test produced a catastrophic failure because of dangerous defects, which were not found despite carefully applied NDE methods, is illustrated in Figures 22 and 23 (Srawley and Esgar, 1966). The 260-inch diameter motor case was fabricated from 250-grade air-melt maraging steel and welded by the submerged arc process. Considerable cracking was encountered, and a manual gas tungsten arc (GTA) process was used for repair. All welds and repairs were inspected very carefully by liquid penetrant, radiography, and ultrasonic methods. The ultrasonic procedure involved the use of compression waves and shear waves in both longitudinal and transverse directions. Cracks were not used in the NDE calibration procedures, but any linear indications were, in all cases, cause for rejection. The motor case failed in hydrotest at



$\sigma_p = 1.1\ \sigma_{op}$ $\quad$ $S.F._w = 0.9\ \frac{\sigma_{yw}}{\sigma_{op}} = 1.3$ $\quad$ BURST AT 60% OF σ_{op}

FIGURE 22. Wreckage of 260 Inch Diameter Motorcase.

Source: Srawley and Esgar, 1966.

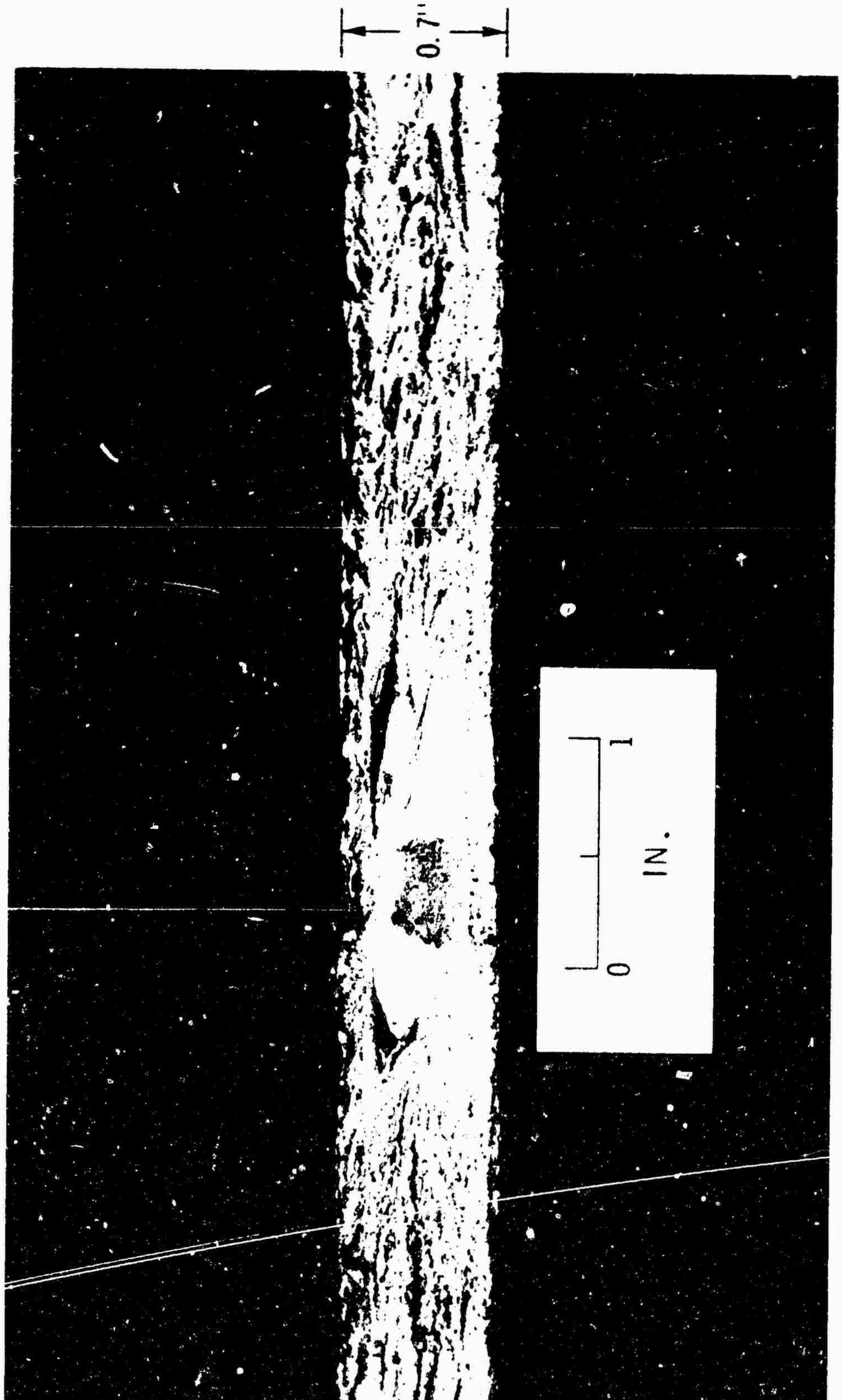


FIGURE 23. Flaw at which Fracture Initiated.

Source: Srawley and Esgar, 1966.

approximately 56 percent of the proof pressure that corresponded to a circumferential stress of about half the design yield strength of the welds. The failure origin is shown also in Figure 23 and is a subsurface defect of substantial size (0.10 x 1.40 in). This defect was located under a GTA "repair" weld that had been produced intentionally in a presumably unflawed region in order to demonstrate that the GTA process did not introduce cracks. Of course, this repair weld was very carefully inspected.

Metallurgical examination indicated that a grain coarsened and embrittled region represented the fracture origin. It is doubtful that this region of weakness could be revealed by any presently known NDE techniques. For this reason, it is important to avoid metal and welding combinations which could give rise to this type of crack-like defect. Generally, the problem may be discovered by bend or tensile tests on welded samples of sufficient size that the produced metallurgical structures would be representative of the full-scale structure.

During the failure investigation of the 260-inch motor case, steel samples were prepared containing fatigue surface cracks of varying depth. These were inspected by various organizations and the results were disappointing both in respect to the reproducibility of rejectable indications among the participants and the ability of the NDE methods to define the actual flaw size.

7. <u>Reliability of NDE Methods</u>

The current information on the accuracy of NDE indications is inadequate. In many cases, theoretical sensitivities are definable, but this knowledge is not too helpful in

determining acceptance criteria. Serious difficulties arise because of flaw orientation or part complexity. At best, laboratory standards provide only first order approximations in calibrating NDI equipment. Often, as in the case of ultrasonics, these calibrations provide absolute reference indications only for specific and simple geometric configurations. In the case of liquid penetrants, the problem of producing crack standards is still unresolved, and the problem of gaging crack depth or shape is generally beyond the capability of current penetrant methods. Therefore, two or more methods may be needed to corroborate or clarify indications. Although, in many instances, flaw indication is sufficient to reject a part, intelligent disposition of complex parts requires more information on flaw size and characteristics. This latter requirement of flaw definition applies primarily to discontinuities. However, not only fine cracks but also precursors of cracking are important. Thus, nondestructive techniques also should be sensitive to material quality (e.g., bond strength, embrittlement). Studies of sensitivities in this context are embryonic, and the appropriate NDE techniques are new and require laboratory development.

a. <u>Accuracy and Sensitivity</u>

It is necessary to know how closely a nondestructive inspection (NDI) indication reveals the true size of a discontinuity. Herein, the accuracy of an NDI method is defined as the precision with which it serves to estimate the actual flaw size, i.e., crack length or depth. Sensitivity may be defi as the ratio of the number of flaws found by the NDE metho the total number actually found or known to be in a (calibration) specimen. Nondestructive evaluation should also discriminate between discontinuities that may cause failure and those that

do not. For example, ultrasonic instruments can be operated at sensitivities that register grain boundaries as well as cracks. However, these grain boundaries may not be as harmful as small cracks, which may be overlooked in the highly sensitive modes of operation.

Comparisons of the relative accuracy and sensitivity of the principal conventional NDE techniques indicate that liquid penetrant, magnetic particle, and ultrasonic methods are roughly equal and consistently superior to X-radiography for surface cracks (for example, Fig. 24). For crack lengths below 0.20 inch, all the previously mentioned techniques showed poor sensitivity (i.e., a ratio of less than unity) in tests conducted with steel and aluminum specimens. Eddy-current inspection was less sensitive than ultrasonics for crack lengths between 0.20 and 0.50 inch. Ultrasonic accuracy is a function of applied tensile stress, and X-ray methods are totally unsatisfactory for small, tight surface-fatigue cracks in steel and aluminum. Production methods are likely to be as sensitive to crack lengths exceeding 0.20 inch as are laboratory inspection methods.

Crack lengths less than 0.20 inch (of the order of 0.10 inch) are considered significant thresholds in aircraft-fracture phenomena. This is well within the theoretical resolution limits of ultrasonics, X-radiography, and other techniques.

In view of the previous discussion, apparently, practical limits may intervene if sensitivity factors of unity are demanded.

b. Round Robin Results

Round robin tests to locate and characterize flaws have been conducted to define the limitations of NDE techniques.

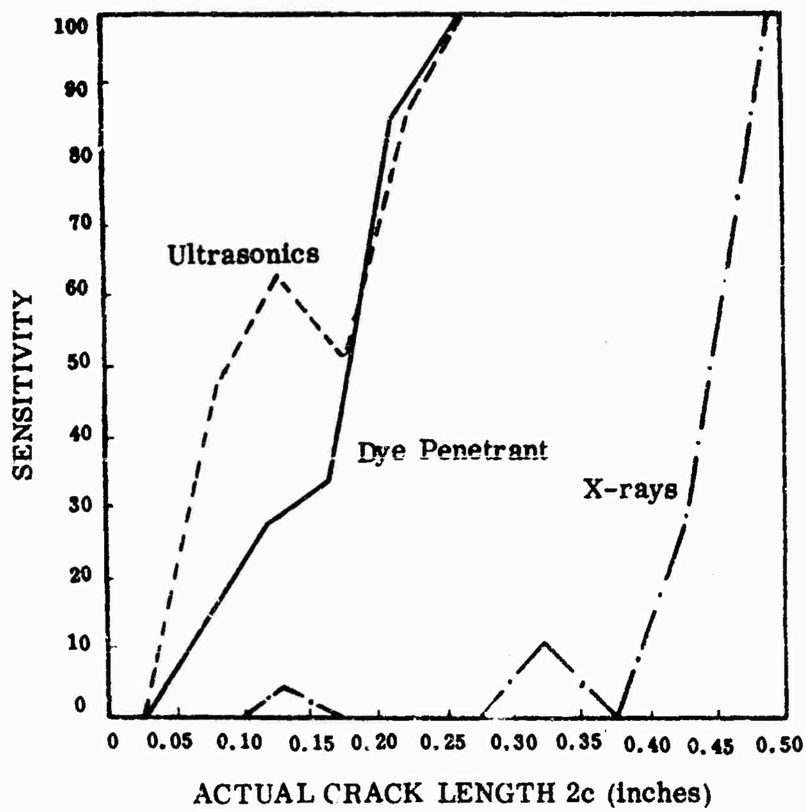


FIGURE 24. Comparison of Sensitivity of NDE Methods in Detecting Surface-Fatigue Cracks in Aluminum.

Source: Packman et al., 1969.

The general finding has been that inspections conducted by independent evaluators tend to disagree. In one instance, the same set of specimens was sent to several different testing facilities for separation into acceptable and rejectable groups on the basis of a certain specification. No two sets of results that were received agreed. Moreover, in every case, each testing organization passed one or more specimens that had been rejected by another organization. This kind of experience is sufficiently commonplace to be anecdotal. The prime causes of this situation appear to be:

(1) inadequate definition in specifications for the NDE method and product-acceptance criteria,

(2) inadequate or nonexistent standards, and

(3) variations in operator qualifications, methodology, or equipment.

Another finding of round-robin efforts is that, in some cases, current NDE methods are much less sensitive and reliable than had been expected, and that there is a great deal more to be learned about NDE for the detection of cracks.

8. Deficiencies of Current NDE Technology

The following general deficiencies in the current NDE technology are recognized:

- The practical potential of presently available techniques is frequently not realized when applied to the problem of finding discontinuities in actual hardware.

- No generally recognized standards exist that permit an estimation of the accuracy and sensitivity of a particular technique.

- There appears to be little progress toward general agreement on how NDE personnel should be qualified. This is largely a problem of training, supervision,

and, above all, motivation both on the part of NDE personnel and also of management.

- Frequently, the potential value of available techniques is compromised by a lack of coordination of hardware flaw with effective NDE requirements and also by a lack of inspectability of the finished product.
- There is no adequate focal point or center of excellence or adequate system for NDE information analysis and retrieval.

9. Specific Problem Areas

Failure mechanisms that have been identified for high-strength structural materials are: fatigue, creep, stress corrosion, oxidation, hydrogen embrittlement, and tensile overload. For these and other conditions that contribute to aircraft failure, advanced NDE techniques and improved methods are needed for both ground maintenance and inflight surveillance. With respect to these factors, the following specific observations concerning the current limitations of NDE technology are recognized:

- Present methods have limited applicability for determining the magnitude and sign of (residual) stresses in a part introduced by manufacturing or service conditions.
- Improved techniques are needed to detect fatigue precursors, follow fatigue progress, and predict fatigue life.
- Adequate techniques have not been developed for the evaluation of thin materials.
- Adequate techniques are lacking for the detection and evaluation of corrosion in hidden areas.
- Current methods generally fall short of giving adequate assurance that joints are free of harmful flaws and have sufficient integrity or strength.

- There is a need for improved NDE methods for detection of flaws and evaluation of key attributes of composite materials and adhesive-bonded structures.
- More extensive application of in situ NDE techniques is required to classify crack initiation and extension signatures.

10. New NDE Techniques

Prominent among the newer and more advanced NDE techniques are those under the general headings of signature analysis and signal or image analysis. Signature-analysis techniques most often involve the interception of phonons or electromagnetic radiations emitted by stress or inmotion parts. Generally, signal and image analysis involves electronic manipulation and computer processing to enhance the information content of the original signals or images. Many new methods simply provide more sensitive and accurate means of obtaining specific information in special circumstances. A review of new NDE techniques for fracture control and prevention follows.

a. Acoustic Emission

Phonon emissions provide potentially powerful tools in real-time monitoring of fracture precursors and failure phenomena. Acoustic or phonon emissions are generated by movements resulting from crack propagations, slip steps, unpinning of groups of dislocations, phase changes, and more subtle micromovements. Generally, the phonons range in frequency from the low audio range to several megahertz. Now, studies are emerging from the infancy stage, and present emphasis centers on the development of instrumentation, methods, and applications. Expanded studies into micro-phonon (high-frequency) emission regions are considered essential for better understanding of

the various mechanisms of failure, especially under extended proof-load conditions.

One of the promising features of the acoustic emission technique is that it can be tuned to monitor selected phenomena in full-scale operating systems. The use of acoustic emission in periodic proof tests should provide useful means for the detection of subcritical flaw growth in actual structures. Flow detection in metals, specifically pressure vessels, can be realized at pressures below yield. This type of NDE is necessarily comparative and uses summations of phonon counts to differentiate flaw size.

A significant feature of acoustic emission testing is due to the irreversibility of the phonon emissions, known as the Kaiser effect. Because of this effect, it is impossible to duplicate or reaccumulate emissions with a given specimen, once it has been stressed. However, if the specimen is reloaded subsequently to high levels, it will begin to emit phonons when the original stress is exceeded. This is an important consideration for service-life evaluations.

It is essential that acoustic emission systems have real-time multichannel capabilities to detect effectively and to locate propagating flaws in structures or components either during structural testing or, in some cases, in a flight test vehicle. Used in this manner, acoustic signatures can be computer processed to warn of critical conditions and to indicate the location of such conditions.

b. Ultrasonic Spectroscopy

A relatively new technique for enhancing the capabilities of ultrasonic and acoustic emission, NDE is ultrasonic spectroscopy. This technique is essentially a signal-analysis technique that compares the acoustic signature of a test specimen to a standard or reference signature, which is characteristic of an acceptable behavior or condition. Work was conducted recently to characterize flaws with respect to their size and orientation within a material. Usually, ultrasonic spectroscopy is performed by impressing "white" ultrasound on an object in a pulse-echo mode and analyzing the frequency spectrum of the return signal. This technique promises to be a sensitive tool for assessing the morphology and mechanical condition of materials. Although little information is available concerning its practical application outside the laboratory, ultrasonic spectroscopy ultimately should provide valuable methods for flaw definition in a variety of situations.

c. Ultrasonic Holography

Ultrasonics and holography are combined for acoustic imaging of the internal condition of test objects. In its present stage of development, ultrasonic holography yields low image resolution and poor image quality. Also, this technique is difficult to apply to large structures, particularly where scanning would be necessary for thorough coverage. Inherent limitations appear to make this technique inappropriate for consideration for fracture detection and control. However, this technique does provide real-time imaging of internal interfaces in a manner not possible with radiographic methods. Therefore, future developments in ultrasonic holography should

be appraised carefully since it may serve as a valuable laboratory tool in fatigue studies.

d. Interferometric Holography

Various methods of interferometric holography have been demonstrated to be very sensitive for discerning static and dynamic microdisplacements of surfaces. Qualitative and quantitative information on subsurface defects is obtained without contact. In interferometric holography, by applying or varying small displacement forces (pressure loads, thermal stresses, ultrasonic vibrations), optical fringe patterns are produced for film or direct viewing in real time. This technique may be considered a means of obtaining and analyzing the mechanical signature of a part or complete machine. Since the fringe patterns are seen superimposed on the object, the static or dynamic microdisplacement of a point on the surface can be located and measured. Using this technique, the vibrational modes and load response of an object may be analyzed. Interferometric holography has been used to detect large flaws in materials and structures. The development of this technique for detecting extended flaws at, or near, surfaces appears feasible, but more study is needed to determine the full potentials of this technique.

e. Thermography

Thermography or infrared imaging is basically a method for characterizing the thermal properties of a part, or structure, through the infrared radiation that it emits. The technique can be applied to microscopic as well as macroscopic areas. The obtained measurements indicate local anomalies or degradation in the inspected object. Since the technique is

comparative, other means should be used with it for absolute measurements. Thermography is essentially a signature-analysis technique which has a potential for rapid survey for incipient failures in large structures. However, this method presently is not well established and may not have the resolution capabilities required for large structure applications.

f. Exo-Electron Emission

For many typical aerospace materials, exo-electron emission may provide a method for the early detection of fatigue damage and prediction of remaining safe life of a material undergoing a fatigue process. This technique can be coupled with acoustic emission for following the formation of surface-slip bands and fatigue-crack extension. However, apparently, exo-electron emission is not ready to emerge from the laboratory.

g. Radioactive Gas Penetrant

Radioactive krypton has been used as a gas penetrant and has demonstrated a capability for detecting microscopic flaws in aircraft materials and component parts. Apparently, on cracks typical of low-cycle fatigue, the gas-penetrant process offers a substantial improvement in sensitivity over liquid penetrants. Since emissions from the absorbed gas penetrate the solid material over appropriate distances, subsurface-discontinuity extensions are detectable. By enveloping or coating the part with photoemulsion, an autoradiograph of the flaw distribution is obtained. This technique is being developed particularly for engine components, manufacturing, and also for maintenance and service NDI problems, provided the parts can be handled for gas penetration and are accessible for inspection.

h. Ancillary Techniques

Pulsed eddy currents, in-motion video radiography, delta and multi-element-ultrasonics, critical-angle ultrasonics, and many other techniques that can be listed are advancing the art and technology of NDE. These may be typed as second or third generation methods that rely heavily on better instruments and advanced microcircuits. Thus, many of the so-called five conventional methods were sophisticated for the more refined needs of subcritical defect recognition and in-flight monitoring. This was accomplished through miniaturization and by improved standardization of probe units especially in terms of their response characteristics. However, an important advance that still awaits realization is the adaptation of refined NDE methods and instruments to nonambient and severe conditions of temperature, pressure, vibration, and so forth.

11. Research Needed

Neither the conventional nor advanced NDE techniques have reached their ultimate utility. Advances in materials technology have created new classes of materials, new assembly techniques, and, thus, new evaluation problems that have not been resolved completely. For improved fracture control and prevention, the principal research and development efforts, noted below, are required.

a. Calibration and Standardization

A common conclusion of recent studies is a need for a comprehensive evaluation of NDE procedures. The majority of currently used equipment was developed using calibration standards that were far from representative of cracks in actual hardware. This has questioned the accuracy and sensitivity of various methods for detecting and measuring cracks. Only

recently, attempts were made to use actual cracks for developing and calibrating NDE instruments. However, more is required than simply the pursual of more discriminating methods employing static crack replicas.

The previously mentioned signature-analysis techniques (e.g., acoustic emission, ultrasonic spectroscopy) require entirely new approaches to calibration and standardization. For example, considerable work must be accomplished to collect and classify acoustic emission signatures generated in forming, welding, assembling, and proof-testing aircraft structures. These in-process signatures should be studied more thoroughly to establish uniform processing parameters and standard acceptance criteria. A prime concept involved is real-time, signal analysis, processing, and feedback to ensure high quality in fabrication. Apparently, research in this area is needed greatly because improper fabrication has been the cause of a large proportion of failures of high-strength structural materials.

b. Material-Integrity Evaluation

An important area for experimental investigation with NDE techniques exists for materials that are essentially coherent or do not contain actual discontinuities of critical or subcritical nature. Nevertheless, serious flaws may exist due to grain boundary films, hydrogen embrittled regions, etc. Generally, these types of flaws are encountered in complex high-strength alloys and, currently, are revealed only by metallurgical examination and destructive testing. Presently, available NDE techniques are inadequate for the purpose of material-integrity evaluation that may be defined as the quantification

or estimation of material-strength properties in the absence of overt discontinuities. Critical angle ultrasonics and ultrasonic spectroscopy are among new NDE techniques that can concentrate on this problem. This is an important area for research since conventional NDE methods are inapplicable. With the development of appropriate techniques, residual or applied stresses are expected to be measured within critical components. Since residual stress may change the strength of the material, the nominal properties are no longer indicative of a structure's ability to withstand an externally applied stress without failure.

c. Inspectability Assurance

More effort is needed in integrating NDE techniques with proof-load investigations. Geometrically similar models of hardware to be tested should be made available for NDE equipment checkout. Particular attention should be given to coordinate structure design and inspection requirements so that inspectability is not compromised by inaccessibility of critical areas to the NDI equipment.

d. Hidden Cracks and Corrosion

Better methods are needed for inspecting around mechanical fasteners. The principal problem for critical applications is ascertaining whether undue stress or localized failure has occurred. Because of the very large numbers of these fastenings, their inspection is costly, and present inspection practices are skimpy. New areas of development should be explored to measure the stress and minimal distortion, or other meaningful attributes characteristic of a proper fastening.

Even after materials and components are assembled and inspected adequately, environmental conditions can cause corrosion

or stress corrosion on portions of the hardware system. When the corrosion is hidden (e.g., around fasteners, undercoatings, between contiguous parts), detection and evaluation become problematic. Radiographic, ultrasonic, and eddy-current methods have been used with varying degrees of success for detection of hidden cracks and corrosion. Better, light-weight, and more versatile equipment is needed for application to a variety of configurations. More investigation should be made of factors contributing to stress corrosion, and better correlation is needed between NDE results and the severity of corrosive attack.

e. <u>Composite Structures</u>

Filamentary composite structures employing high-modulus materials in plastic matrices are coming rapidly into use in sophisticated applications in advanced aircraft. Development of suitable NDE methods will require preparation of optimum test standards that structure and material characteristics and discontinuities can be determined. Low-energy radiography and ultrasonics are promising techniques for evaluating composite structures relative to fiber bending, porosity, and delaminations. However, no current NDE technique has been developed and investigated satisfactorily for use with composites, and continuing effort is needed for improve correlations between inspection data, physical-mechanical properties, and service performance.

f. <u>Thin Materials</u>

The employment of thin materials in aircraft presents special NDE problems since conventional inspection techniques tend to be inapplicable, particularly under industrial or field service conditions. In some cases, as materials become thinner, the size of the significant flaw decreases correspondingly.

Low voltage radiography, high frequency and Lamb-wave ultrasonics, and high frequency-eddy currents have been employed with thin materials. Although most methods have been laboratory tested, improved methods and instrumentation are needed.

g. Fatigue

By the very nature of fatigue, little can be done to detect it prior to service. However, improved knowledge of fatigue precursors should lead to the development of NDE methods for the detection of the precursors. Then, vital components could receive periodic examinations at critical stress points to detect precursors, the beginning of fatigue, or to check the progress of any allowable fatigue. After a crack has formed, most of the conventional NDE techniques can be applied. Although some work has been performed in this area, most work has been with simple laboratory fatigue specimens.

Probably the most advantageous course to follow is periodic examination of complex structures for precursors or impending fatigue cracks. For this purpose, ultrasonics, acoustic emission, eddy current, and other techniques must be made more quantitative. Of course, the techniques must be applied by instrumentation refinements that permit NDE at assembled structures. Considerable work must be accomplished in this most vital area of fracture control.

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APPENDIX E

METAL IMPROVEMENT

Appendix E

CONTENTS

METAL IMPROVEMENT

1. Information Requirements

Projections of the potential for improvement in fracture properties of high-strength metals require consideration of metallurgical and mechanical factors. Sequential analyses should be evolved, as follows:

a. consolidation of scientifically valid data,

b. generalized interpretation of the data in terms of fracture-mechanics parameters,

c. deduction of basic relationships between metallurgical and mechanical aspects,

d. examination of the factors that determined technological advances in recent years, and

e. definition of credible limits for additional advances by the application of principles deduced from these analyses.

New research tools may be cited as contributing to recent advances. These include: (1) fracture-mechanics procedures for definition of macromechanical properties, and (2) the development of electron microscopes for the examination of micromechanical aspects of metal-grain plastic-flow and rupture processes. These tools have revolutionized the potential for scientific approach to fracture-properties improvement. However, the development of modern metal-processing methods (vacuum-arc melting, etc.) provided the translation of research knowledge to practice. High-purity metals (clean with respect to nonmetallic phases), which previously could be produced only in "pound lots," now can be produced commercially in large quantities.

The discussions will center on the separation of high-strength metals into the categories of the old conventional materials versus the new premium materials. The feasibility of attaining additional improvements must be analyzed in terms of particular metal systems, strength levels, and section sizes.

2. Micromechanical Aspects

Continuum-mechanics theory provides no basis for rationalization of the factors that determine the microfracture response of the metal-grain structure to a specified state of mechanical constraint. The theory predicts that, with increase in crack size, there is an increase in mechanical constraint to plastic flow. In principle, the development of a plastic zone at a crack tip should follow stress-strain relationships that are specific to the applied constraint-state. With increase in the degree of constraint, an elevation of the flow curve applies to the crack tip, as compared to a tensile-test bar. Accordingly, higher levels of crack-tip stress are required to produce a unit increment of localized crack-tip strain. The stress level may act to develop "abnormally" high grain deformation. The constrained metal acts as if it had increased "stiffness," compared to the tensile-test case.

The consequences of high stresses, required to produce crack-tip plastic flow, can be understood only in terms of micromechanical metallurgy. The high stresses promote microcracking at noncoherent boundaries, such as exist at the interfaces of metal grains and nonmetallic inclusions. Similar effects are developed at hard-phase (carbides, etc.) boundaries. The microcracks, evolving from such foreign phases, join to produce premature rupture of crack-tip plastic zones, as compared to

"clean" metals. Cleanliness is defined as a condition of low density of noncoherent grain-boundaries.

As the metal grains are strengthened (high yield strength), microcracking at the above described points of grain-structure discontinuity is accentuated. Thus, the problem of metallurgical improvement of the metal-grain structure, for purposes of increasing fracture resistance, is minimizing the number of initiation points for grain-structure microcracking.

Mechanical constraint is defined orginarily in terms of crack-front dimensions. For example, a <u>through-thickness</u> crack features a constraint <u>level</u> or <u>capacity</u> that is a function of the section size. Level and capacity are equivalent terms, because they are related to the degree of inhibition of plastic flow that evolves with increase in crack-front dimensions. One fracture-mechanics definition of constraint refers to the plane-strain state, i.e., "the capacity of the crack to enforce plane-strain conditions."

With increase in metal-grain ductility, there is an increase in plastic-zone size as the K_I stress-intensity is increased. If the plastic-zone size exceeds plane-strain limits (small sizes), the crack tip is blunted. Thus, constraint relaxation evolves and elastic-plastic (K_c) conditions apply. Through-thickness yielding then begins to develop. With additional increase in metal-grain ductility, the constraint-relaxation effect is accentuated, and plastic fracture results.

Fracture mechanics defines three fracture states as follows:

a.	plane strain	(K_{Ic} or K_{Id})
b.	elastic-plastic	(K_c)
c.	plastic	(over-yield for fracture extension)

In the discussions to follow, only strength-induced changes in constraint states will be considered. The temperature-induced effects (for steels) are not covered. Thus, all statements relating to steels will be based as being "on shelf," i.e., above the temperature-transition range.

There are two factors that may cause a change in fracture state:

a. changes in section size for a specific metal (metal-grain ductility fixed), and

b. changes in metal-grain ductility (constraint-state fixed).

Both aspects will be analyzed by the procedures to be defined.

The following broad generalizations apply:

a. Low-strength metals undergo large crack-tip plastic flow, despite high elevation of flow curves due to high level constraint. Thus, microcracking is developed only after constraint-relaxation has evolved. The metal behaves in a ductile fashion.

b. Ultra-high-strength metals cannot undergo large crack-tip flow even for conditions of relatively low elevation of flow curves due to low level constraint. Microcracking sites affect crack-tip ductility only within narrow limits. Generally, the metal behaves in a brittle fashion.

c. Intermediate-strength metals may develop large or small degrees of plastic flow for conditions of elevation of flow curves. The specific constraint capacity and the relative concentration of microcracking sites determine if brittle or ductile behavior ensues.

3. Macromechanical Aspects

Systematization of metal properties data, for purposes of rationalizing metallurgical factors, requires consideration of all three possible regimes of fracture resistance--plane strain elastic-plastic, and plastic.

Of these, only plane strain is subject presently to rigorous characterization and analytical treatment. Nevertheless, it is essential to record any reasonable engineering parameter that identifies the metal states of elastic-plastic and plastic fracture. The alternative is to record only plane-strain (K_{Ic}) values and relegate all metals that do not fall into this low level of fracture resistance to the "limbo" of nonmeasurable fracture properties.

Limiting data to the plane-strain state precludes adequate analysis of fundamental relationships between fracture properties and metal-grain structures. In fact, metallurgical "successes" become unrecordable, while metallurgical "failure" (brittleness) is recorded exactly. The scientific literature on fracture research presents voluminous data for brittle metals in terms of K_{Ic} parameters, largely for the same general types of metals that can be defined as classical fracture-mechanics "research" materials. The engineering field cannot afford to limit data surveys to purely brittle metals. Metal improvement practices that elevate a particular metal from plane strain to elastic-plastic and then to plastic levels of fracture resistance (for a specific section size) must be recognized. The utilization of metals, featuring fracture properties above the plane-strain state, is a separate question and a matter of engineering decision on a case basis.

The possible evolution of crack-opening displacement, J-integral, or other potentially analytical methodologies does not preclude using currently available means for characterization of elastic-plastic or plastic fracture states. At the minimum, fracture-mode transition, crack-tip lateral contraction, or energy-to-fracture may be used as criteria of gradations of ductility levels above the plane-strain state. Of these, energy-to-fracture is the most easily determined parameter of increasing metal ductility.

4. Procedure for Integration of Mechanical and Metallurgical Factors

The primary requirement for any integration-system is the development of relationships between strength and fracture-states for specified conditions of constraint (section size). If the strength scale is plotted as shown in Figure 25 then other scales may be added to index the fracture characteristic of a metal for a given yield strength. Analyses of the significance of compilations of fracture properties (data bank), must be made by superimposition of a reference grid derived from fracture-mechanics principles. Metallurgical aspects are defined by additionally superimposed zoning as to "generic" types of metals. In this respect, the definition of "generic" is made best by principles of physical and process metallurgy.

Figure 25 presents an introductory form of the Ratio Analysis Diagram (RAD) for steels. The dotted area of this figure is simply a compilation of a large body of valid K_{Ic} data for steels, produced as plates of 0.5- to 4.0-inch (12.5 to 100mm) thickness. Thus, the range of attainable K_{Ic} values is indexed in relation to the yield strength scale.

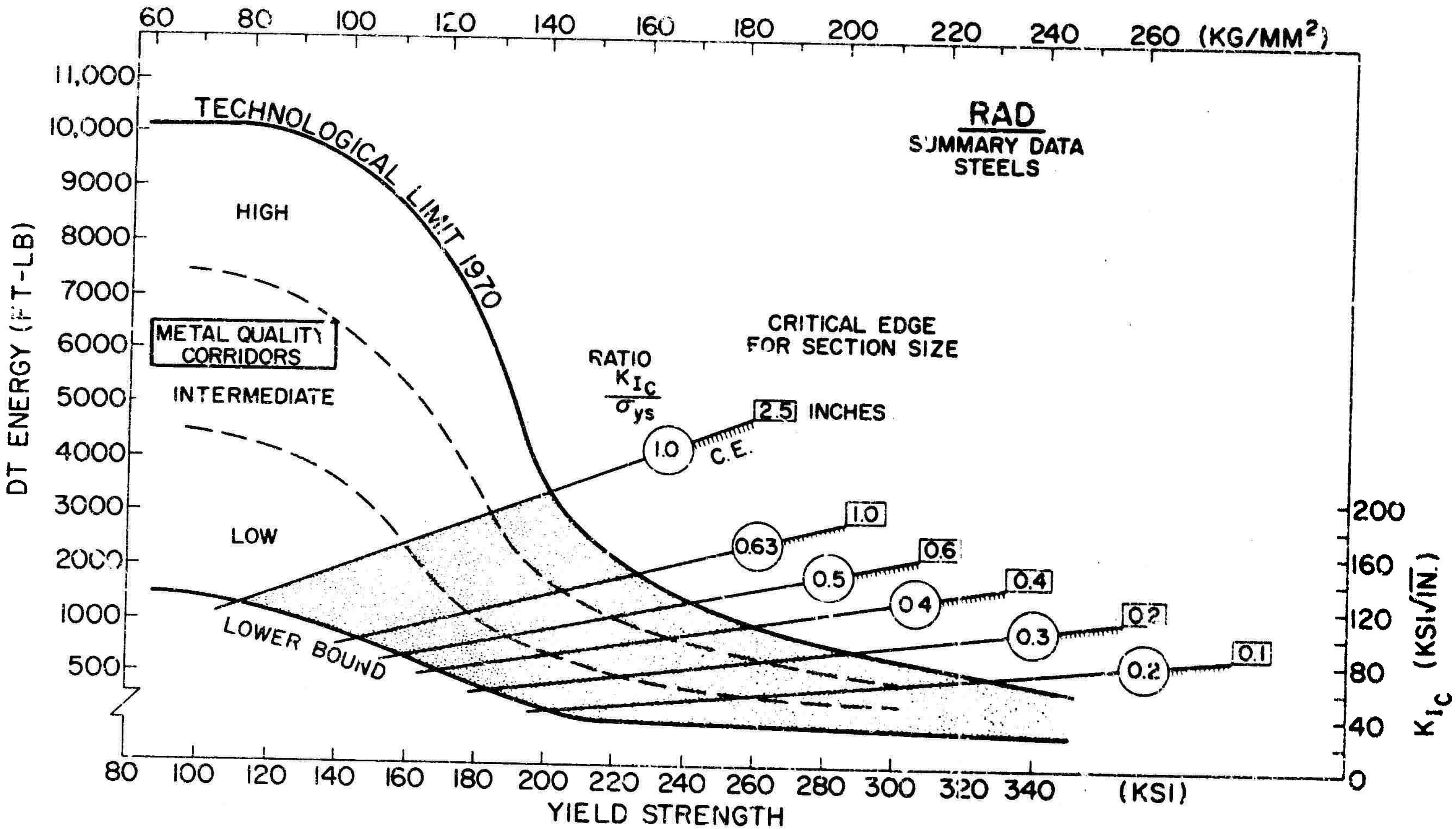

FIGURE 25. Standardized Ratio-Grid System which Provides for Analysis of the Plane-Strain Limits of Specific Section Sizes. Each of the ratio lines represent a "critical edge" of transition to elastic-plastic fracture, for the noted section size.

Source: Naval Research Laboratory.

A grid system of K_{Ic}/σ_{ys} ratio lines then is superimposed on the data bank. This grid provides the basis for fracture-mechanics interpretations. The first interpretation is the limit of K_{Ic}-measurement for a specified section size. This is indicated by the section-size designations that are indexed to specific ratio lines. For example, a plate of 1.0-inch (25mm) section size is limited to a 0.63 ratio-measurement capacity by the size of the K_{Ic}-test specimens that can be cut from the plate.

The K_{Ic} test-specimen is designed that the crack front attains <u>maximum</u> constraint capacity for the involved section size. In the case of a 1.0-inch (25 mm) K_{Ic} specimen cut from a plate of the same thickness, the constraint capacity is the same as developed for a <u>through-thickness</u> crack in the subject plate. The test specimen "models" the condition of maximum constraint and, therefore, the lowest level of fracture-extension resistance possible for that plate in a structure. The metal cannot behave in a "less ductile" manner.

The constraint-capacity limits, expressed by the ratio lines, thus define the limits of plane-strain fracture for the specified section sizes. Metal of slightly higher <u>intrinsic</u> plane-strain properties than metal,defined by the ratio limit for the section size,will undergo "constraint-relaxation." Therefore, the fracture will be of nonplane-strain type (elastic-plastic). With additional increase in intrinsic plane-strain fracture properties, the fracture becomes of plastic type. The RAD reference to the grid lines is always in terms of the intrinsic plane-strain properties. Constraint-relaxation is defined as the specific plane-strain property that must be exceeded for the section size of interest.

The unique aspect of the RAD is that the slope of the K_{Ic}-yield strength relationship for a metal of specified metallurgical quality provides for extrapolation "up and down" scale. Thus, ratio values that cannot be measured for a specific section size may be deduced by the trend-line relationships, as will be explained. Therefore, the impasse that exists as to measurement of K_c or plastic properties is bypassed by the trend-line method. Continued indexing to the plane-strain scale provides a reference of known significance.

The critical-edge (C.E.) ratio lines for transition from plane strain to elastic-plastic fracture correspond to the plane-strain ratio limits for the section size, as noted in the figure. In simple terms, the reader should consider the fracture characteristics of a steel of specific section size as being

a. Plane strain if the data point in the RAD falls below the referenced ratio line, and
b. Elastic-plastic if it falls moderately above the line.

The referenced line is the "critical-edge" demarcation between plane-strain constraint and the beginning of constraint relaxation for the section size of interest.

Continuing with consideration of K_{Ic} data (the dotted area of Fig. 25), the existence of three metal-quality corridors should be noted. These corridors are related directly to the degree of "cleanliness."

Low, intermediate, and high, as noted in the diagram, relate to the density of nonmetallic phases, such as oxides, sulphides, carbides, etc. These are phase particles that can be seen and counted at high magnification.

Apparently, the highest attainable K_{Ic}/σ_{ys} ratio level for a specified yield strength depends on the "corridor quality" of the steel. Other deductions include:

a. a shift to lower yield-strength ranges for <u>retention</u> of a given ratio value, with decrease in corridor quality;

b. a shift to lower yield-strength ranges for <u>increase</u> in ratio value, within a specified corridor;

c. the transition of thick sections from plane strain to elastic-plastic, at lower levels of yield strength as compared to thin sections, and

d. K_{Ic}- value insensitivity to increasing yield strength above 200 ksi (140 kg/mm^2) for steels of low-corridor quality.

The significance of the Dynamic Tear (DT) test scale may be deduced by considering the close similarity of this Navy standardized test to a side bend 1.0-inch (25mm) K_{Ic} test. The same section size and deep sharp crack are used. Therefore, the same mechanical constraint is applied in testing of the metal. In the region below the 0.63 ratio line, the 1.0-inch DT-test fractures in plane strain. In the region above the 0.63 ratio line, the fracture becomes mixed-mode and then full-slant type. The energy-to-fracture reading is a faithful reflection of the <u>degree</u> <u>of</u> <u>constraint</u> <u>relaxation</u> that has evolved above the limit of plane strain for this section size.

A 1.0-inch (25mm) K_{Ic} specimen would "track" the rise of the K_{Ic} value (if a specific steel were heat-treated from very high to decreasing values of yield strength) following the

course of one of three quality corridors. When the ratio line 0.63 is reached, K_{Ic} measurement is no longer possible. At this point the continued use of the K_{Ic} test is assumed plus a measurement of fracture energy. Then, the increase in fracture energy with decreasing yield strength will track the quality corridor to its highest plastic-fracture levels. Since the 1.0-inch (25mm) DT test features the same constraint capacity as the K_{Ic}-test specimen of the same section size, the DT test may be substituted as a less expensive method of tracking this rise to elastic-plastic and plastic fracture levels.

Extensive correlations have been evolved between DT energy values and K_{Ic}-test data, leading to positive documentation that an entry point from the DT energy scale easily predicts the K_{Ic} value (measured by valid ASTM procedures) within a ±15 ksi $\sqrt{in.}$ range. These correlations include a large number of valid K_{Ic}-test data obtained for 2- to 3-inch (50 to 75mm) thick specimens. Thus, it is possible to index K_{Ic} values that would require the use of very large K_{Ic} specimens.

The fracture energy bears a direct relationship to the measurable K_{Ic}/σ_{ys} ratio for section sizes that provide the necessary level of plane-strain constraint. Briefly, the same <u>intrinsic</u> increase in metal ductility results in

a - increased K_{Ic}/σ_{ys} ratio if adequate constraint is imposed, or

b - increased mixed-mode fracture energy if the constraint is inadequate.

The two effects are relatable and rationalizable in fracture mechanics terms.

To summarize, the two-scale entry system of the PAD provides for a full spectrum view of the effects of yield strength and metal quality on fracture states. These effects must be analyzed in terms of section size, and the ratio-line grid-system provides this reference.

The DT scale is not intended to replace the K_{Ic} scale. It is intended to permit matching the high and low ends of the fracture properties range for analysis purposes. To do this, both scales can be used within reasonable agreement in the transitional regions where ratio values climb from 0.5 to 1.5 value. The match is made in this region and, therefore, corridor or trend-band curves may be "carried through" from low to high ends of the RAD without interruption. The match is entirely adequate for these purposes.

The most important aspect of the DT-test scale is that it provides an inexpensive method of determining two crucial engineering factors at low cost, as follows:

a - the corridor quality of the metal, and

b - the ratio-value index.

Thus, by locating a DT-test data point at the appropriate yield strength, these features will be disclosed. Then, extrapolations "up and down" the corridor can be made for section-size analyses of fracture states. This information is developed at a cost of approximately ten dollars compared to several hundred dollars for a K_{Ic} test, if a valid value is attainable. The DT test reports the RAD location in all cases, whether or not the section size provides for plane-strain conditions. In brief, its value is to make feasible the use of the K_{Ic} scale and grid system at bearable costs, for most purposes.

5. Extensions of RAD Interpretation Capabilities

The ratio-lines grid also provides for indexing crack size-stress relationships, when plane-strain conditions apply. Figure 26 illustrates a generalized graphical plot of such relationships, referenced to K_{Ic}/σ_{ys} values, for long thin and stubby crack geometries. From this plot, it is possible to deduce the critical crack depths (a) for specific levels of relative stress. This information may be transferred to the RAD ratio-lines grid.

This added information is indicated in Figure 27 for the case of long thin cracks and two levels of relative stress. The assumed section size of interest is 1.0-inch (25mm) thickness. Thus, the surface-crack interpretations are limited to the level of 0.63 ratio.

The importance of this analysis system is that the benefits evolving from metallurgical increases of K_{Ic} values are immediately evident in terms of elevations to higher ratios and related increases of critical crack sizes. The practicing design engineer or metallurgist does not have to ponder on what an extra 10 or 20 ksi $\sqrt{in.}$ achievement in metal properties signifies. In some cases, it may mean increases in critical crack sizes of only a few thousands of an inch. In other cases, it may mean increases in the order of several tenths of an inch. The relative level of K_{Ic}/σ_{ys} and the relative stress being considered decide how much "return" there is for the metal improvement.

Figure 27 also indicates the best present estimate of the transitions in fracture states for plate of 1.0-inch (25 mm) section size. The following reasons are cited for locating the elastic-plastic region in the range of 0.63 to 1.0 ratios.

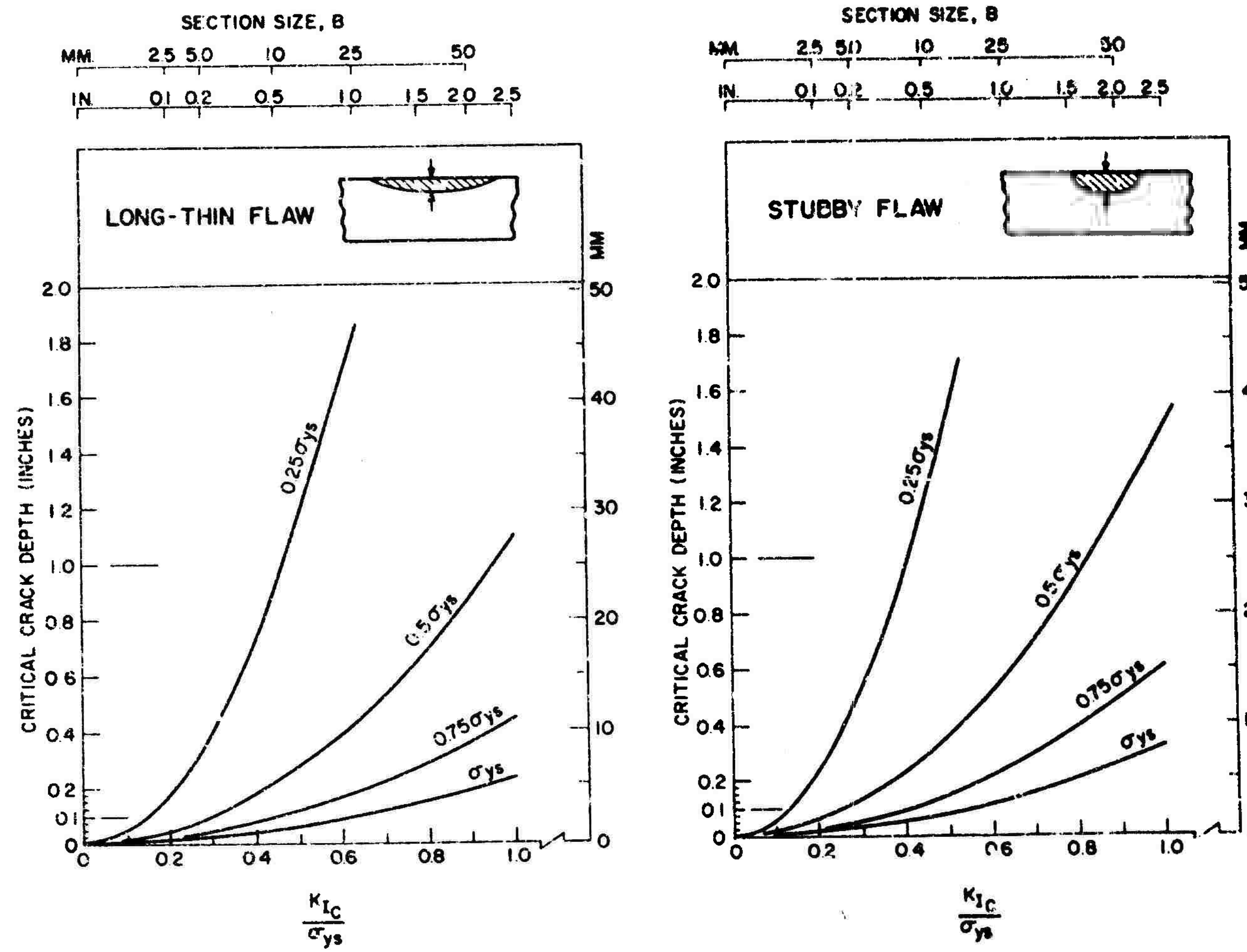

FIGURE 26. Graphical Summarization of the Effects of Increasing K_{Ic}/σ_{ys} Ratio on the Critical-Depth of Surface Cracks. Indicates relationships to four levels of relative stress and two extremes of crack geometry. The β scale (above) denotes the minimum section size required for measurement of specific ratio-values. Steels.

Source: Naval Research Laboratory.

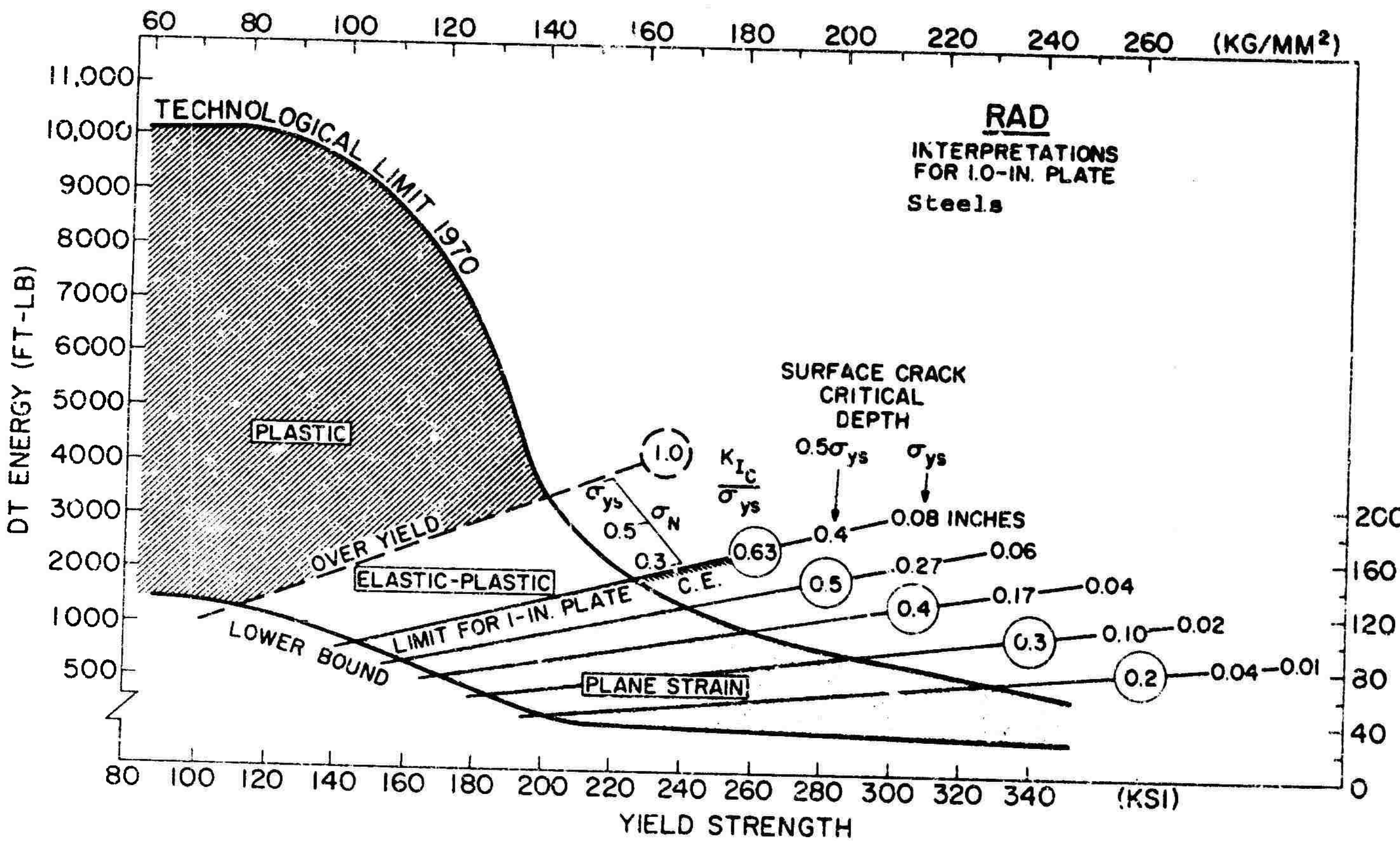

FIGURE 27. Analyses for 1.0-in. (25 mm) Section Size. The 0.63 ratio line defines the plane-strain limit and the 1.0 ratio line references the yield criterion. The relative-stress scale, inserted in the elastic-plastic region, defines the stress level required for fracture extension of a through-thickness crack (2 to 3T length). Critical crack-depths, for two levels of relative stress, are coded to ratio lines in the plane-strain region (see Fig. 2b relationships).

Source: Naval Research Laboratory.

a. Fracture Mechanics Rationale

1) The critical edge transition from plane strain to elastic-plastic fracture is defined by the requirement that $B \geq 2.5\ (K_{Ic}/\sigma_{ys})^2$ for plane-strain constraint. On this basis, plane-strain conditions are exceeded above the 0.63 ratio level.

2) The transition to plastic fracture is defined by the "yield criterion," based on the relationship $B \cong 1\ (K_{Ic}/\sigma_{ys})^2$. Section sizes that feature this low degree of constraint relative to plane-strain requirements are expected to develop pronounced through-thickness plastic flow (constraint-relaxation) for through-thickness cracks. This degree of constraint-relaxation is considered to be conservatively sufficient to require nominal stresses of over-yield levels. On this premise, plastic-fracture conditions are attained at the 1.0 ratio level of intrinsic metal properties.

3) The unattainability of 1.0 ratio levels for the 1.0-inch (25mm) section size is the basis of the fracture-mechanics yield criterion. Intrinsic metal properties that require a 2.5-inch (62mm) section size for measurement of plane-strain fracture resistance (1.0 ratio) should result in pronounced constraint relaxation for section sizes of 1.0 inch (25mm).

b. Experimental Observations

1) DT tests of 1.0-inch (25mm) section size show pronounced degrees of mixed-mode fracture and through-thickness deformation (lateral contraction) at RAD positions equivalent to 1.0 ratio levels.

2) Explosion-tear tests of large (20- x 24-inch or 500 x 600mm) plates of 1.0-inch (25mm) thickness, featuring

through-thickness 2T, 2.0-in. long (50mm) cracks, show flat break (elastic-stress fracture) at RAD positions equivalent to 0.63 ratio and lower. However, pronounced deformation (general yielding) is developed at RAD positions equivalent to 1.0 ratio level and higher.

3) The fracture appearance in the explosion-tear tests is exactly the same as that of the DT test, i.e., the same degree of mixed-mode fracture and lateral contraction.

4) These observations apply to steels, titanium, and aluminum alloys.

The explosion-tear test performance clearly validates the fracture-mechanics definition of the yield criterion. In fact, the criterion appears conservative, as claimed.

Based on this extensive experimental evidence, it is proposed to accept the fracture-mechanics definitions for the lower and upper bounds of the elastic-plastic region, as follows:

1) Lower bound - as the critical-edge, plane-strain limit for the section size, i.e., $B \cong 2.5\ (K_{Ic}/\sigma_{ys})^2$.

2) Upper bound - as the ratio line for the section size that is calculated from the relationship $B \cong 1\ (K_{Ic}/\sigma_{ys})^2$.

On these bases, the conservative "widths" of the elastic-plastic regions, in terms of ratio span above the critical-edge, are as follows:

Section Size	Approximate Span
0.3- to 0.5-inch (7.5 to 12.5mm)	0.2 ratio
0.5- to 1.0-inch (12.5 to 25 mm)	0.3 ratio
2.5- to 3.0-inch (62 to 75 mm)	0.5 ratio

The upper and lower bound-indexing procedure of the elastic-plastic region for the case of 0.5-inch (12.5mm) section size is illustrated in Figure 28. Comparison with Figure 26 indicates that the elastic-plastic region is shifted to a higher yield-strength range, approximately 20 ksi (15 kg/mm^2) higher as the result of reduction in section size from 1.0 to 0.5 inch (25 to 12.5mm).

The elastic-plastic region for 2 5-inch (62mm) section size, Figure 29, features a lower bound of 1.0 ratio and an upper bound of 1.5 ratio. The elastic-plastic region is shifted to approximately 30 ksi (20 kg/mm^2) lower values for the thicker section size as compared to the 1.0-inch (25mm) section size. A total shift to approximately 60 ksi (40 kg/mm^2) higher levels is indicated for decreases in section size from 2.5 to 0.5 inch (62 to 12.5mm). The attainment of elastic-plastic properties at higher yield strengths of thinner sections is an important structural-design consideration.

Conversely, when the plane-strain state is achieved for thinner sections, the <u>limiting</u> K_{Ic} values are lower compared to thick sections. Thus, the best attainable plane-strain properties become those of the "more brittle" type and decrease with section size. Note that the range of critical surface-crack sizes for thin sections is much smaller compared to thicker sections. Fortunately, the attainment of elastic-plastic properties becomes metallurgically "easier" with decrease in section size.

Figures 27, 28, and 29 also introduce the use of a relative stress scale that indexes the level of nominal stress required for fracture extension of through-thickness cracks

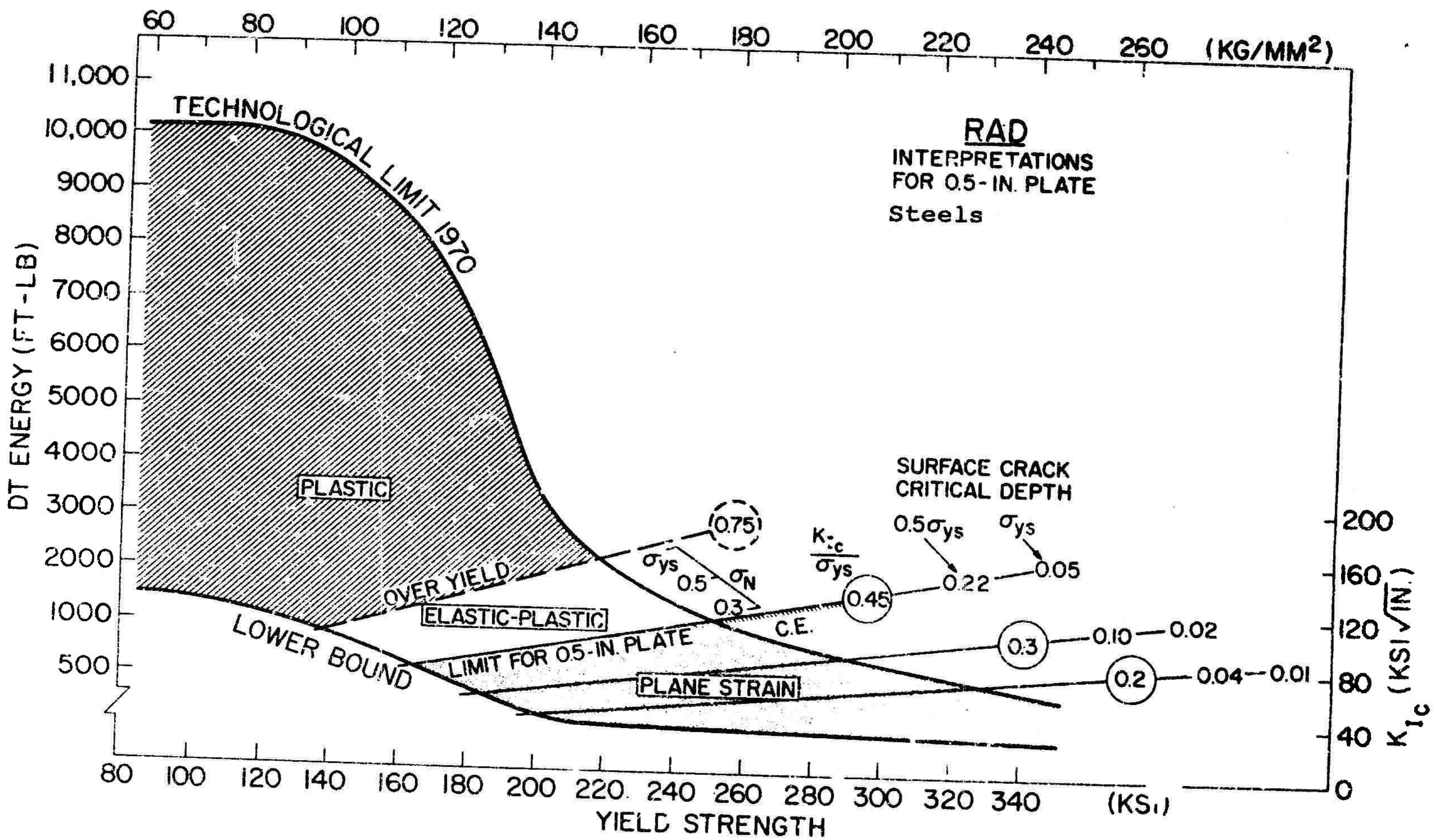

FIGURE 28. Illustrating RAD Procedures for the Definition of Fracture-State Properties of 0.5-in. (12.5 mm) Section Size. A standardized coding is used.

Source: Naval Research Laboratory.

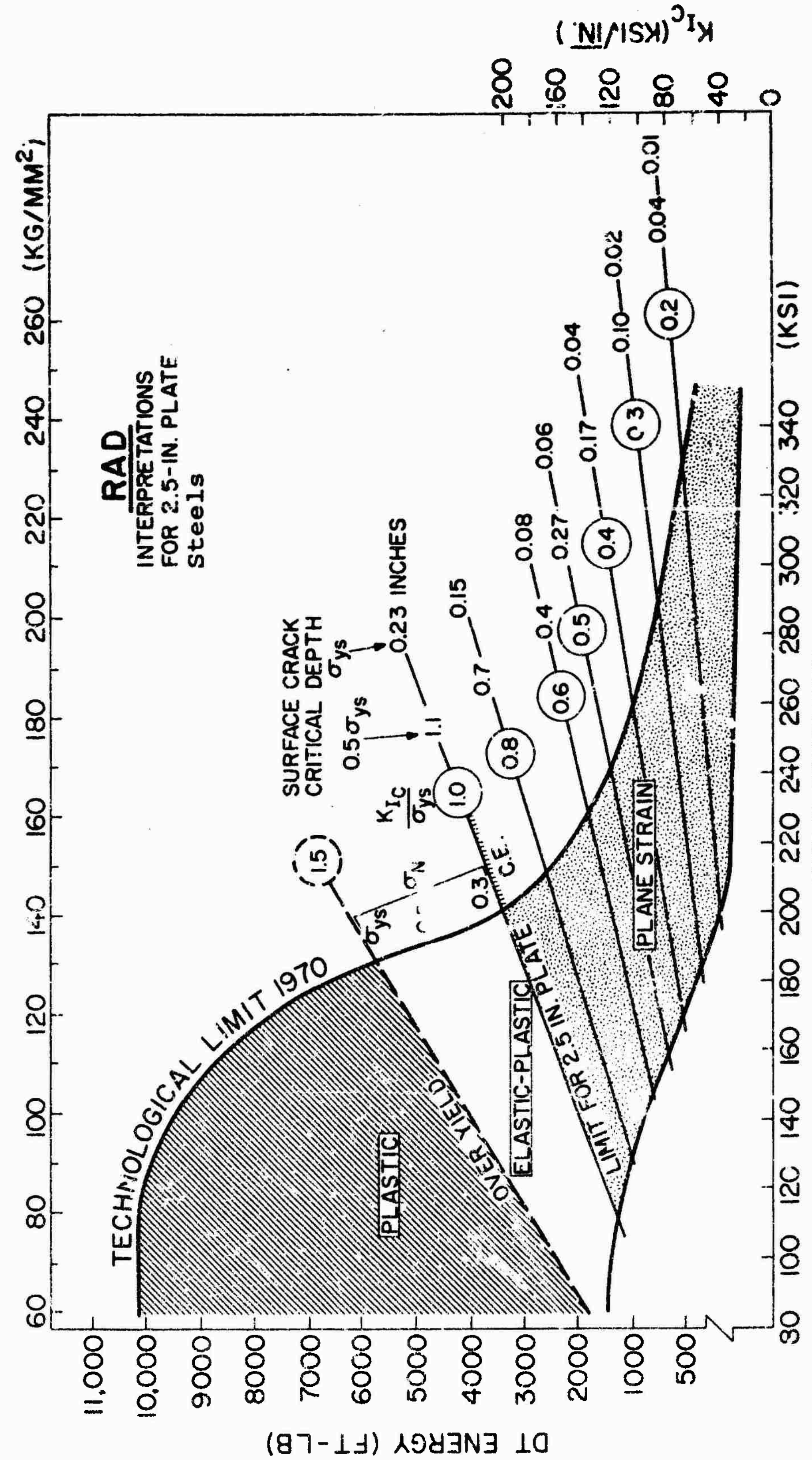

FIGURE 29. Analyses for 2.5-in. (62 mm) Section Size.

Source: Naval Research Laboratory.

(2 to 3T length). The derivation of the lower limit (in the order of 0.2 to 0.3 σ_{ys}) is evolved by calculation of the stress level, required for fracture extension of such cracks, at the plane-strain limit (critical edge) for the section size. The σ_{ys} level, noted at the upper bound of the elastic-plastic region, is evolved from definition of the yield criterion. A 0.5 σ_{ys} index is obtained by simple interpolation.

There should be little concern for the absolute accuracy of this inserted scale. Note that the technological limit curve indicates that the transition from 0.3 to 1.0 σ_{ys} levels must evolve in a 30 ksi (20 kg/mm^2) strength range. Since the elastic-plastic transition region is very narrow, any attempt to provide more exact definitions will require analyses of statistical variances of metal properties (to be discussed). In brief, the scale suffices for the analysis of behavioral trends to be discussed and for the generalized description of the structural significance of the elastic-plastic region.

6. Metal Quality Corridors

The metal-quality corridor relationships, noted in Figure 25, were evolved from extensive studies at the Naval Research Laboratory from 1962 to the present. These studies were the basis of Navy high-strength steels development programs and involved the purchase of a wide variety of experimental and commercial steels, produced to specified melting practices. The intent was to control "cleanliness" aspects so that the effects on fracture resistance could be defined. Ordinarily, the large heats involved were rolled to plates ranging in section size from 1.0 to 4.0 inch (25 to 100mm).

Figure 30 presents selected data from these studies that are of particular importance to aircraft structures. The data include the most advanced types of quenched and tempered steels (such as the 10-8-12, 9-4-20, 9-4-30) and also maraging grades. Large heats were made by the melting practices noted in the figure. Heat-treatment studies were conducted to define the optimum procedure for developing the highest fracture toughness for yield strengths in the range of 160 to 220 ksi (112 to 155 kg/mm^2). The specific aim was to determine if the level of fracture resistance, for plates of 1.0 to 3.0-inch (25 to 75mm) section size, could be elevated from plane strain to at least elastic-plastic properties in this yield strength range.

The resulting trend bands, indicated in Figure 30, clearly document that optimizing of heat treatments for a specified yield strength can increase fracture resistance only to the "ceiling level" dictated by metal-cleanliness factors. In other words, the "ceiling" is built into the metal by the melting and deoxidation procedures. The relative cleanliness of the metal "in the ingot" becomes the determining ceiling-factor thereafter.

This is a most important deduction. It signifies that a small section of an ingot may be forged and evaluated as to "corridor quality." Since a large ingot may be priced at $2 to $3 a pound and a large forging at $10 to $20 a pound, rejection of undesirable material at the ingot stage is an economically justifiable procedure.

The tremendous span of fracture-resistance properties of steels in the 180 to 220 ksi (125 to 155 kg/mm^2) yield-strength range is made clearly evident. For example, at 200 ksi

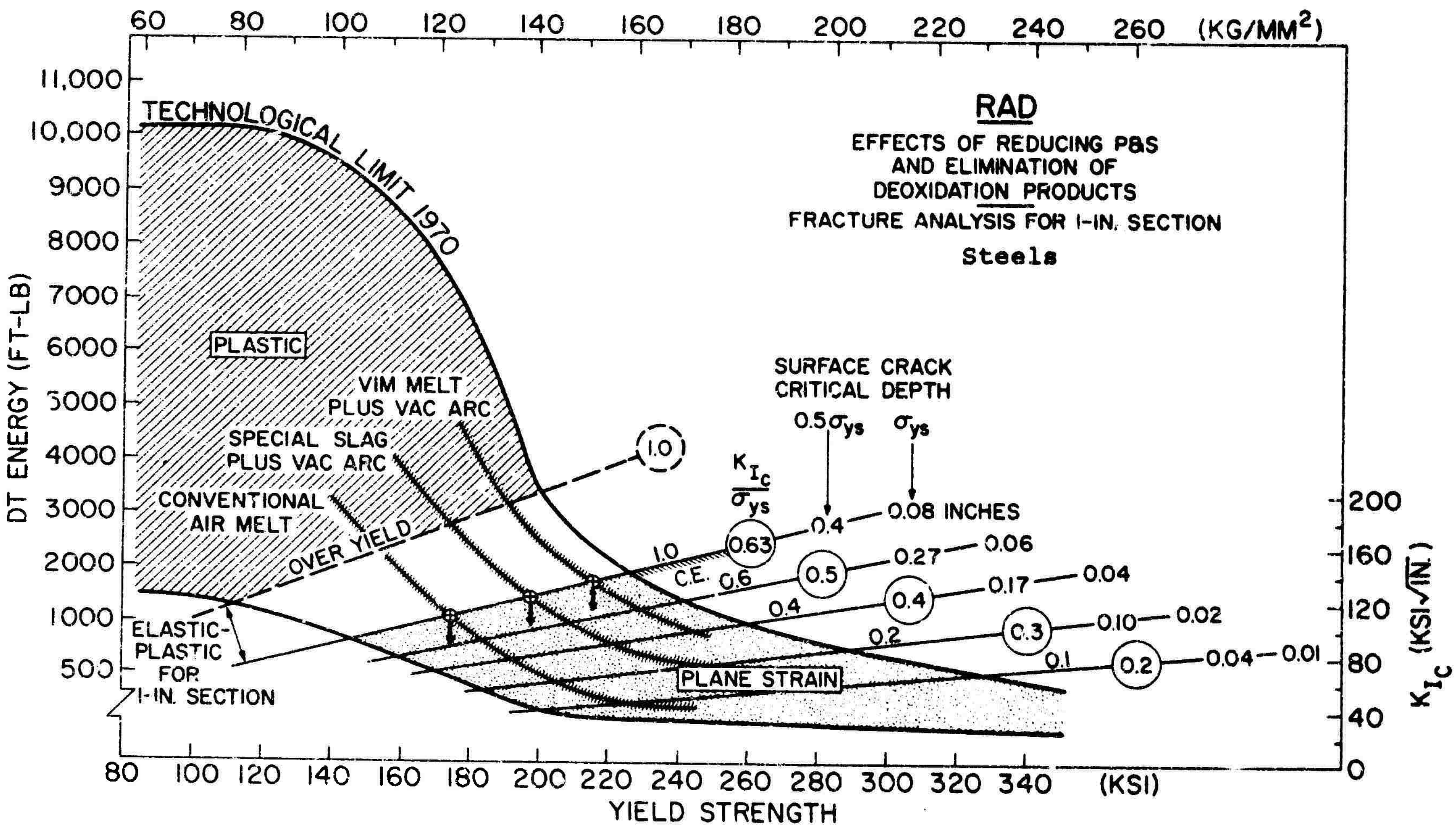

FIGURE 30. Trend Bands which Illustrate the Effects of Relative Metallurgical-Cleanliness Relatable to Furnace-Melting and Deoxidation Practices. Fracture analyses, for 1.0-in. (25 mm) section size, provide an index of the significance of the metallurgical improvements.

Source: Naval Research Laboratory.

(140 kg/mm^2) yield strength, a 1.0-inch (25mm) plate may have elastic-plastic properties if of high cleanliness, have 0.63 ratio properties if of intermediate cleanliness, and have very low 0.3 ratio properties if of conventional cleanliness. The corollary effects on critical crack sizes are enormous, as indicated by the RAD-indexing of this aspect.

The reader may analyze the larger range of effects for the 180 ksi (125 kg/mm^2) level of yield strength. At this level, a 1.0-inch (25mm) plate may vary between plastic, elastic-plastic, and low ratio values, as a function of corridor quality.

The melting-practice variables, discussed above, related specifically to the "new" steels. The reader should not believe that the "older" varieties necessarily can be elevated to such high corridor positions. Thus, it is essential to expand on the discussions of metal-cleanliness aspects.

There are two basic origins for void-site nucleation phases in steels. These are:

a. extrinsic (foreign) nonmetallic particles that may be traced to melting and deoxidation practices, and

b. intrinsic (inherent) nonmetallic particles, resulting from the formation of carbide phases during solidification, particularly for steels of high-carbon contents.

The improved steels that were developed during the past decade, and notably during the past five years, feature intermediate or low-carbon contents to promote improved weldability. Hardenability and strength aspects are controlled by sophisticated use of alloy elements with avoidance of excessive

dependence on the use of high-carbon contents, characteristic of the "older" steels. As such, the problems of intrinsic carbide phases were eliminated from consideration.

These new steels have the potential of attaining high metal-quality corridor positions, if the introduction of other types of nonmetallic phases is avoided.

The melting-practice effects for the new steels are described as follows:

a. Conventional air melt. Limited slag treatment results in relatively high P and S contents (>0.015%). On solidification, phosphide and sulfide phases are formed. Aluminum, or other deoxidation practices to remove oxygen, result in the Al_2O_3 or other nonmetallic phases. Thus, the void-site density is high.

b. Special slag, plus vacuum-arc remelting. Multiple slag-melting practices are used to lower P and S levels. Vacuum-arc remelting lowers oxygen content, thus eliminating the need for other deoxidation treatments cited above, and causes a degree of metal-grain refinement. The void-site density is decreased to intermediate levels.

c. Vacuum-induction melting, plus vacuum-arc remelting. Generally, melting starts with an air-melt charge of special low P and S iron. Three or more slags may be used to lower P and S to very low levels. Alloy additions are made under vacuum, and the oxygen content is controlled by carbon-deoxidation effects. The metal that undergoes the final vacuum-arc remelt is of very high purity. If properly processed, these steels are

very clean, even when examined under the microscope at high magnification, i.e., very few nonmetallic particles can be seen.

7. <u>Metallurgical Variance Questions in K_{Ic} Zone</u>

When a steel is purchased to a specified minimum yield strength, a range of yield-strength and fracture properties will be present in the population of the production lot or lots. The range of statistical property variations depends on the specification controls that are applied.

(O) <u>ordinary</u> metallurgical control, based on specification of composition and heat treatment-wide range,

(T) <u>test control</u>, aimed at narrowing the property range by rejection--within feasible limits, relatable to cost, and

(TL) test-limit control, established by test reproducibility.

For example, yield-strength values for steels of over 170 ksi (120 kg/mm^2) level, may range as follows:

(O) 20 to 30 ksi (15 to 22 kg/mm^2)

(T) 10 ksi (7 kg/mm^2) - strict control

(TL) 5 ksi (3 kg/mm^2)

In the following discussions, ordinary (O) limits will be considered. The reader may further analyze the effects of reducing the range to (T) or (TL) limits on decreasing the sizes of the "statistical boxes" to be described. For guidance, K_{Ic} test variations, in ASTM round-robin tests by different laboratories, were determined to be in the order of ±10 percent. Therefore, this range is representative of the (TL) limits for K_{Ic} control.

Figure 31 presents a typical (O) ordinary variance statistical box that may be expected, if a forging-grade steel is

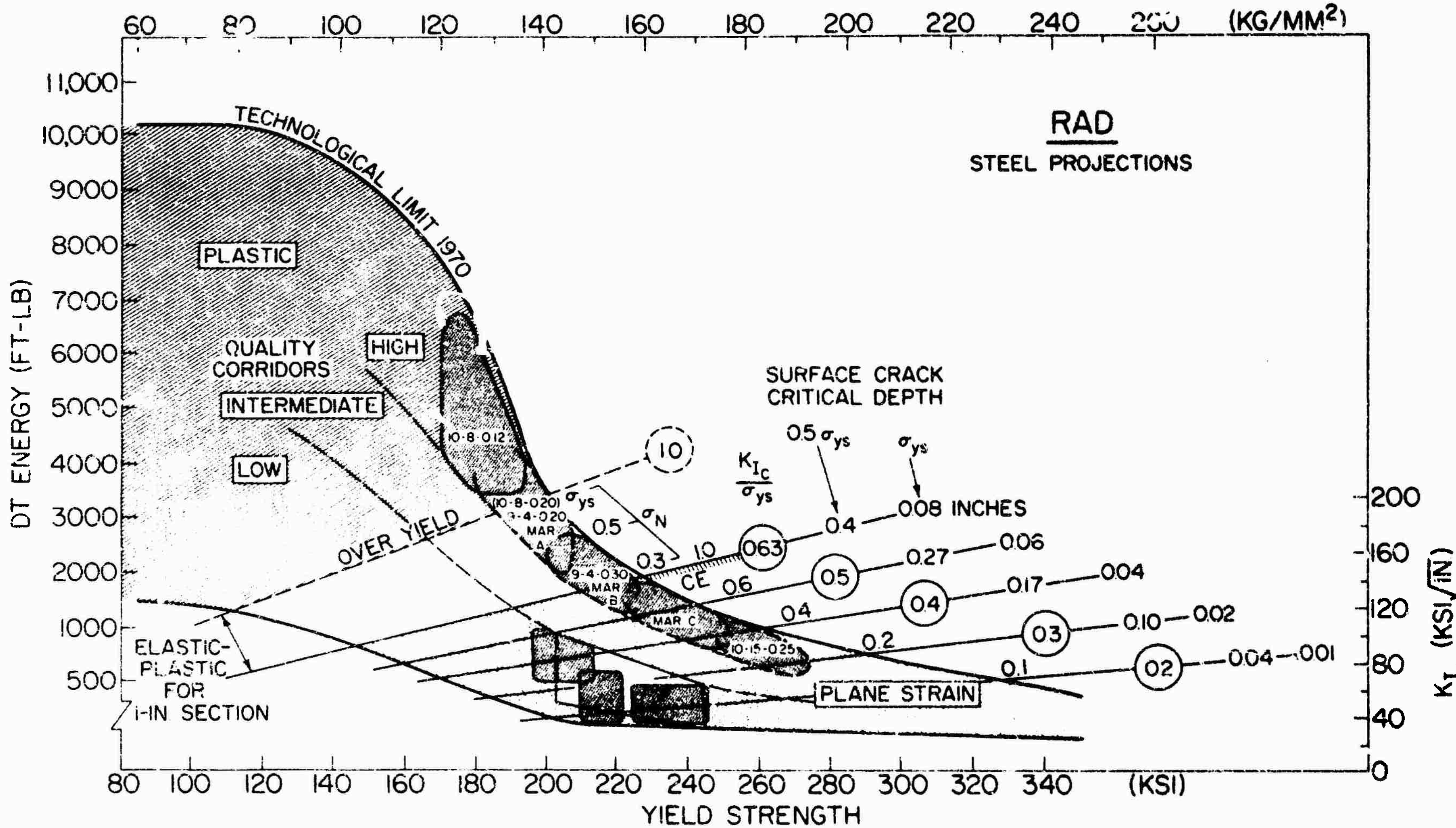

FIGURE 31. RAD Zoning for the New, Premium-Quality High Strength Steels.

Source: Naval Research Laboratory.

procured to minimum yield-strength specifications of 200 ksi (145 kg/mm^2) and if one of the following additional aspects apply:

a - air-melt practices are used for the "new" steels, or

b - the carbon content of the older, conventional steels is sufficiently high to result in forming persistent alloy-carbide phases.

Either of these aspects result in the presence of nonmetallic phases that promote early void initiation during the process of crack-tip plastic zone growth. Thus, plane-strain fracture properties will be limited to low values. In effect, a low corridor "ceiling" is imposed on the metal.

In the example shown in Figure 32, the steel is assumed to be a conventional forging grade of the "older" variety, i.e., intrinsic alloy-carbide phases are present, aspect "b" above. Thus, the lowest ceiling level is imposed, as noted in the figure. This information provides for locating the ordinary variance (O) statistical box. This is a predicted box, in advance of any specific tests. The box may slide to lower levels by off-optimum heat treatments and/or decreasing temperatures. This aspect is shown by the lower dashed box.

The following additional predictions emerge:

a. Smaller statistical boxes may be achieved by the use of (T) procedures to (TL) limits.

b. The (TL) limit provides the smallest possible box and is in the order of one-third the (O) box shown in the figure. It cannot be made smaller.

c. The exact location of the smaller box is defined by the minimum yield-strength level within the box (see Fig. 33 as an example).

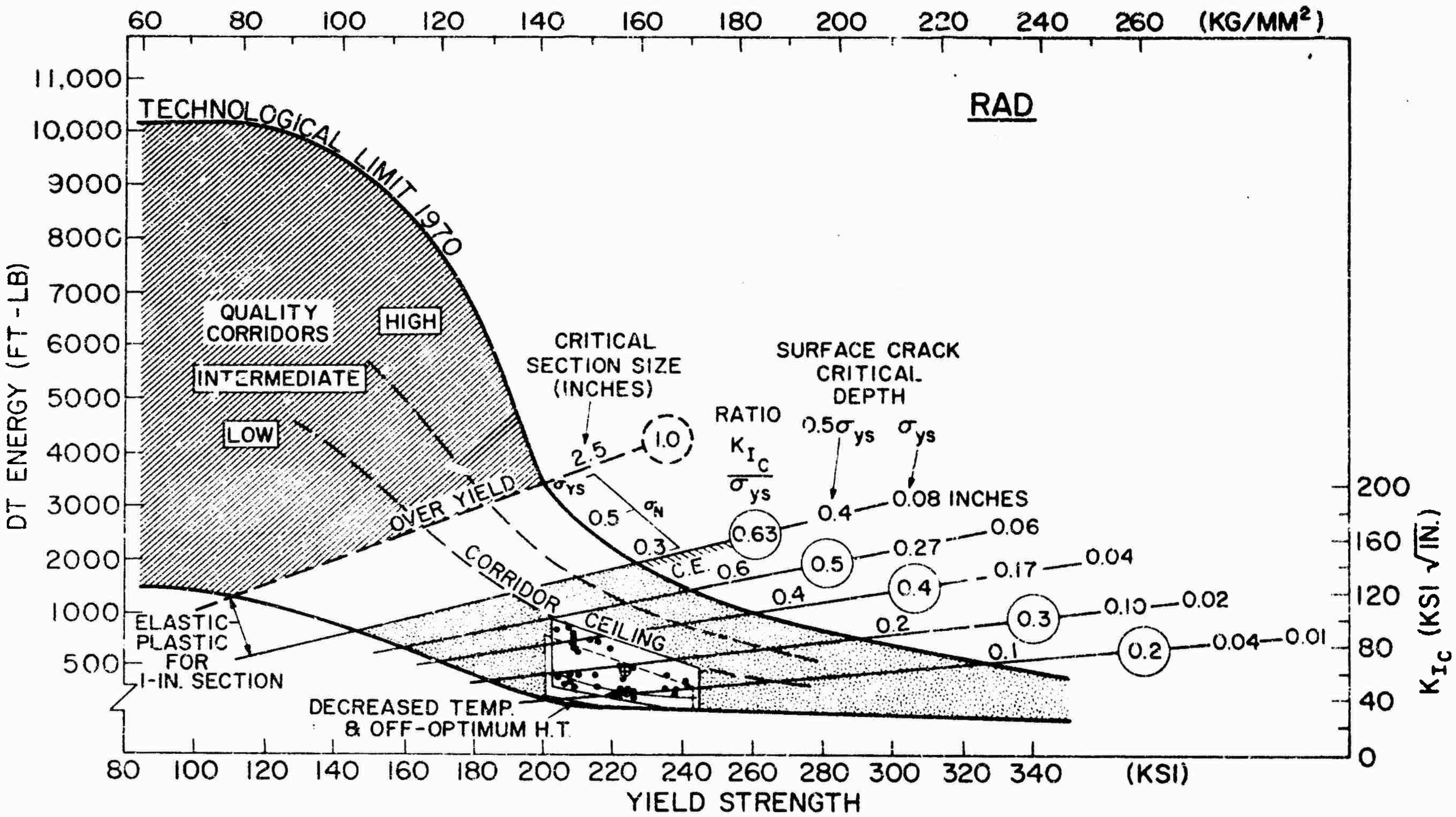

FIGURE 32. Statistical-Box Estimate for a Low Corridor-Quality Steel, Purchased to Minimum Yield-Strength Specifications of 200 ksi (140 kg/mm^2). These advance predictions have been documented to be highly accurate, in cases that extensive statistical-testing was performed.

Source: Naval Research Laboratory.

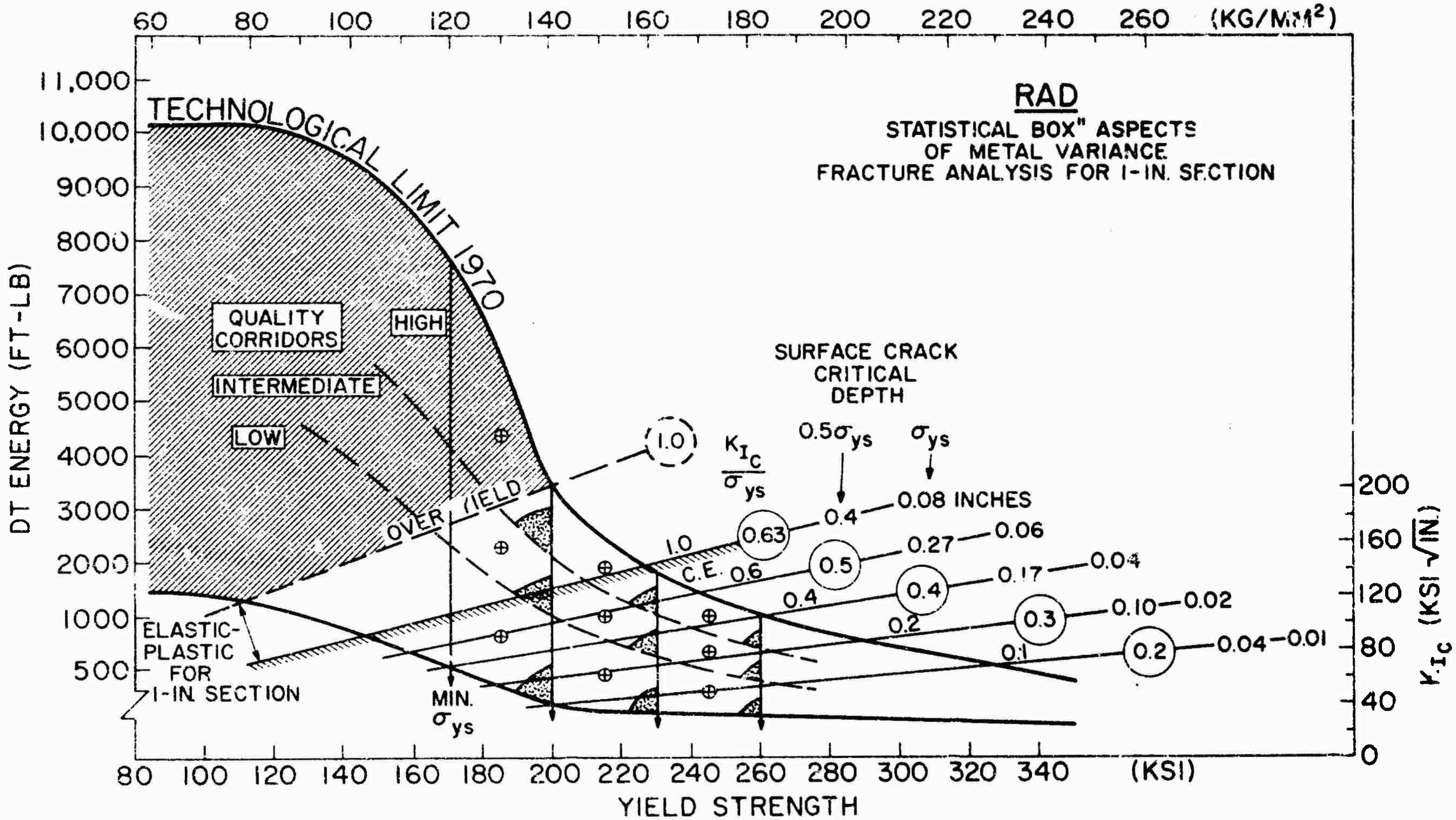

FIGURE 33. Statistical-Expectancy Boxes, for Steels Purchased to Four Levels of Minimum Yield-Strength and to Three Levels of Melt Quality. The crossed points denote the average expected-properties. The dotted corner-regions indicate the minimum levels of fracture properties that can be specified, or used in design.

Source: Naval Research Laboratory.

These generalized predictions may be made for any box location in the RAD. In the case of Figure 30, the minimum yield strength and metal quality were selected so that they related specifically to the F-111 wing-structure metal. Thus, the tremendous effort expended in K_{Ic}-testing and heat-treatment variables research in the F-111 program could be used as a check of the RAD predictions. The following conclusions emerge:

a. The data points, shown in Figure 30, are the F-111 data, based on the original (O) limits.

b. The smaller boxes, shown in Figure 31, document the decreases in box sizes attained by using (TL) control practices.

c. Note the slope (trend line) of the boxes shown in the subsequent figure. A significant increase in K_{Ic} level was attained <u>only</u> by cutting back on the yield strength minimum. This aspect is predicted fully by the slope of the lowest corridor.

Those predictive deductions could not have been made prior to 1970.

8. <u>Application of Statistical Box Concept to K_{Ic} Specifications</u>

The "statistical box" indicates that design and purchase considerations must include deciding on appropriate <u>lower bound values</u> for K_{Ic}. This is a function of the yield strength level as well as the narrowness of the yield strength range. If the lower bound is placed at a relatively high K_{Ic} level for the population, it would result in eliminating a large fraction of the metal, as produced.

Now the statistical population question will be examined in a broader context, Figure 32. The figure illustrates the statistical "boxes" expected from purchase to various levels of minimum yield strength and metal quality. We estimate an

ordinary (O) yield-strength range of 25 to 30 ksi (18 to 22 kg/mm^2) above the specification minimum, as the base of the box, and a K_{Ic} ratio variance of two ratio lines as the height of the box. The latter is a conservative estimate. The (+) points indicate the mean expected values for yield strength and K_{Ic}.

The predicted location of these boxes, for conventional, intermediate, and best quality steels must increase in average value (+), following the trend of the strength transitions for the respective quality corridors. The lower bound K_{Ic} values that must be used in design, or would be acceptable to the producers, lie in the lower corner regions of the boxes (dotted semicircles). There is little increase in the lower bound values for the conventional steels, with decrease in yield strength, until levels of less than 180 ksi (125 kg/mm^2) are specified as minimum values. On the other hand, the lower bound value is increased rapidly by decreasing the minimum yield strength below 230 ksi (160 kg/mm^2) for the high quality, clean steels. Decreasing the yield strength range to (T) or (TL) limits does not change these conclusions.

The increases become most significant when the lower bound K_{Ic} value approaches the ratio-measurement limit for the section size. However, this means that steels, which feature a lower bound K_{Ic} and lie close to the limiting-ratio values, may be used (and purchased) only if most of the population have fracture-resistance properties that K_{Ic} measurements are not possible. This is the case if the plate section sizes are used at the "as purchased" thicknesses in the structure. If considerable machining is performed, ratio values in excess of the final section-size limits may be specified and measured. However,

the fracture characteristics of the "thinned" sections may then be of elastic-plastic type. These aspects are analyzed easily by the RAD.

The analyses of metallurgical variance pose practical questions that emphasize the value of close control of metal-quality factors and heat-treatment procedures. If the (O) metallurgical control limits are not adequate, then it is necessary to resort to metal-rejection procedures.

Irrespective of the point of rejection, prior to or after purchase, the cost of rejection is assumed by the user. These analyses indicate that close to 50 percent rejection is necessary if K_{Ic} values, equal to or exceeding the (+) mean points are established as the purchasing criteria. Decreasing the size of the statistical box only results in shifting the (+) point. On a relative basis, the rejection statistics will continue to apply.

Decreasing K_{Ic}-level requirements to 20 ksi $\sqrt{in.}$ below the (+) points will reduce rejection rates an estimated 20 percent or less. However, the effects of such reductions on the critical crack sizes, and, therefore, inspection feasibilities must be considered. In general, the related <u>decrease</u> in critical crack depths for regions of high stress are of minor order because the critical flaws are exceedingly small, if stress levels are high. If inspection limits are exceeded for the case of the higher K_{Ic} value, further reduction by 20 ksi $\sqrt{in.}$ is practically insignificant because there is little to lose additionally.

The analyses for regions of low stress are entirely different. Decreases of 20 ksi $\sqrt{in.}$ may be highly significant

with respect to inspection requirements. The related decreases in critical crack depths may be in the order of tenths of inches, depending on the population (+) level. The most direct procedure for analyzing the effects of decreasing (or increasing) lower-bound K_{Ic} values is by reference to the ratio. Decreases that signify a 0.1 ratio drop from 0.6 to 0.5 have a completely different meaning from those of 0.3 to 0.2 The RAD coding to critical crack sizes clearly indicates these effects for intermediate and relatively high stress levels.

These analyses also disclose the benefits that can be derived by shifting from low level-corridor metals to the high cleanliness metals of highest corridor features. Again, the benefits derived from such increases in K_{Ic} values for the regions of high stress are not appealing particularly.

The reasons for such unfortunate projections do not evolve solely from metallurgical variance factors. They are basic to fracture mechanics theory, see Figure 26.

The benefits in metallurgical improvements that result in exceeding the ratio-line limit for the section size can be analyzed in terms of traversing the elastic-plastic regime. The structural significance of entering, and then exceeding, this regime is considered best by reference to the stress level required for extension of a <u>through-thickness</u> <u>crack</u>, as follows:

a. At the plane-strain limit for the section size, the level of elastic stress for extension of such cracks is relatively low--in the order of 0.2 to 0.3 σ_{ys}.

b. As the plane-strain limit is exceeded, the elastic-stress level requirement <u>increases</u>

because of the larger plastic zones evolving from constraint relaxation. Stresses in the order of 0.5 σ_{ys} and then of higher level will be required for relatively small degrees of constraint relaxation.

c. With increasing constraint relaxation, the stress required for extension of a through-thickness crack will exceed nominal yield level. This degree of constaint relaxation may be defined as the "yield criterion" above which plastic fracture evolves.

The degree of metallurgical improvement that results in crossing through the elastic-plastic regime for a specified section size pays high dividends in terms of rapidly raising the nominal required stress for extension of through-thickness cracks. The resulting benefits to structural reliability are evident in this context because the nominal design stress is a readily definable structural parameter. Moreover, the high costs, evolving from attempts to locate minute flaws that are critical for high-stress regions, are eliminated. Modest increases in metal costs for purposes of avoiding the plane-strain state can pay high dividends, cost- and safety-wise.

The types of trade-off analyses that may be made between yield strength and metal-corridor levels are indicated by the generalized RAD presented in Figure 34. The options that may be examined by the engineer are indicated by the solid black squares and the arrows. The design-strategy "plotting board" aspects of the RAD thus are indicated. The analyses can be performed in a few minutes, once the RAD is understood.

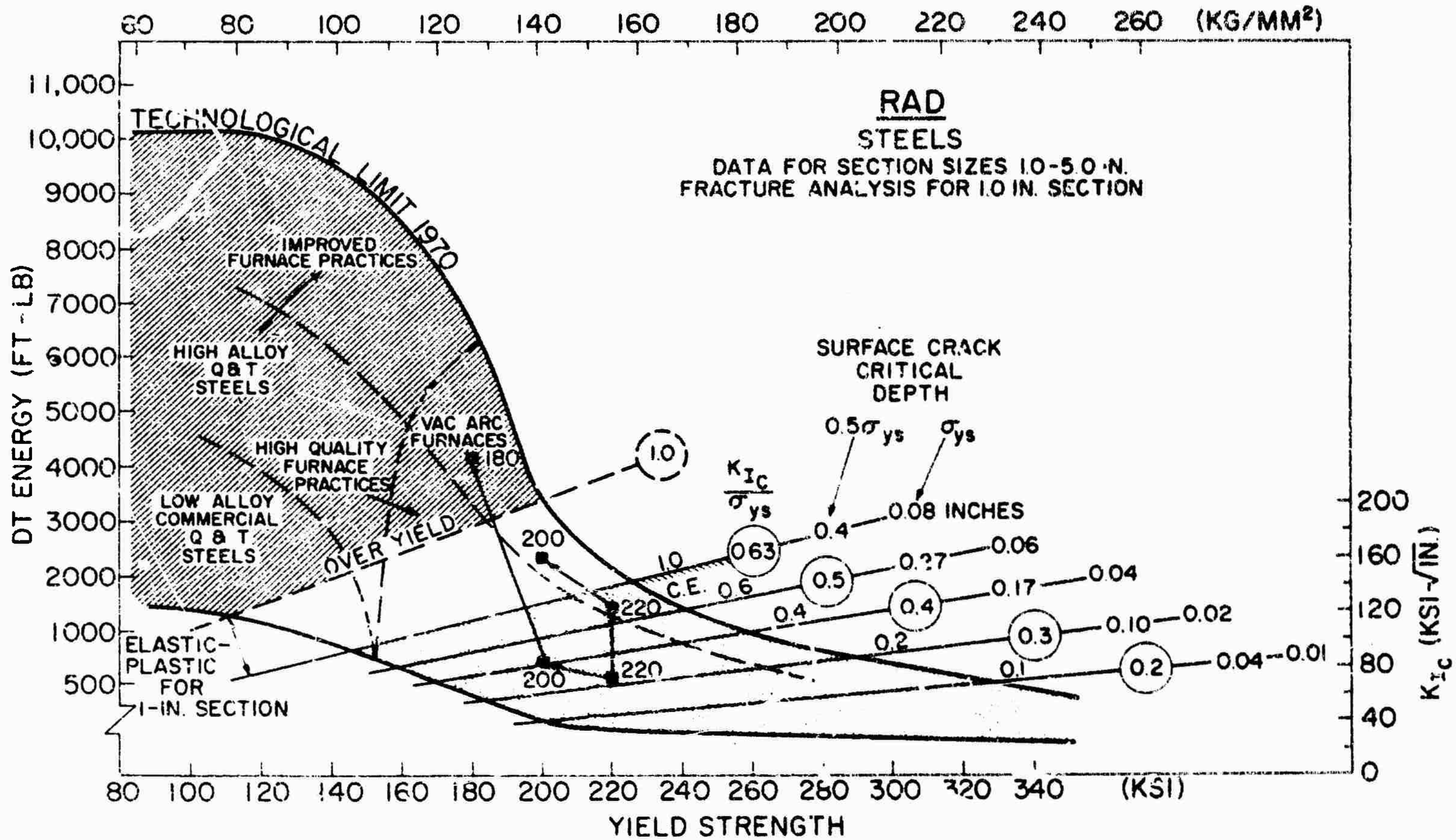

FIGURE 34. One Form of More-Detailed Metallurgical Zoning of the RAD. Finer zonal-definitions, of primary interest to metallurgists, can be evolved depending on the metallurgical-analysis purpose. The trade-off analyses that may be made in design are indicated by the lines with arrows. Combination of these two types of analyses leads to highly sophisticated designs.

Source: Naval Research Laboratory.

Figure 33 compares the location of the statistical-expectancy box for the low corridor-ceiling steels of Figure 31 with those of a "chain" of the new premium steels of high-ceiling features. The chain evolves by modification of alloy contents to provide increasing levels of strength. The steels are strength limited by the basic alloy formulation, i.e., they are specifically designed for the indicated strength ranges. In general, it is not feasible to evolve compositions that span a very broad range of strength levels because off-optimum microstructural conditions result.

The mechanical-state analyses, presented in Figure 31, are specific to 1.0-inch (25mm) section size. However, the K_{Ic} scale-referenced properties, noted for these steels, are attainable over the range of 0.5 to 3.0 inch (12.5 to 75mm). Specific types may be adjusted by alloying to provide the same properties for greater thickness.

The reader may now "exercise" the RAD by defining the elastic-plastic regions for different section sizes. For example, the elastic-plastic region for the 0.5-inch (12.5mm) section size moves to considerably higher yield-strength ranges compared to that of the Figure 31 plot. The specific section size, <u>as used</u> in the structure, should be the basis for these deductions. Thus, different parts of a structure may feature different fracture-state properties, if the section size varies. In aircraft wing-box structures, the variations may be from 0.5 to 3.0 inch (12.5 to 75mm) or greater. Thus, the fracture state can vary from plane strain to plastic depending on strength-level selections.

9. Relationships to Design Requirements and Cost Factors

The hull structures of submarines and naval vessels, compared to the "box structures" of swept-wing aircraft, provide a basis of comparison. The following aspects of similarity and difference are of primary interest to these analyses:

a. Submarine and Ship Hulls

(1) Section sizes are 1.0 to 3.0 inch (25 to 75mm) or greater.

(2) Cost of fabricated construction is limited severely to $4.00 to $10.00 per pound, depending on the structure.

(3) Because of cost limitations, fabrication details are relatively complex (stress concentrations are high).

(4) Requirements include the ability to withstand plastic deformation at "hard points," irrespective of the presence of potential cracks. Therefore, plastic fracture properties are desired.

b. Aircraft "Box Structures"

(1) Section sizes are 0.5 to 3.0 inch (12.5 to 15mm).

(2) Cost of fabricated construction is allowed to rise as required and may be over $1,000 per pound for critical components.

(3) Accordingly, fabrication details may be refined highly (stress concentration minimized).

(4) Requirements do not include the ability to withstand plastic deformation in the presence, or absence, of cracks. Therefore, elastic-plastic fracture properties may be expected to provide a high degree of protection.

The differences illustrate why lower strength crack-resistant steels of plastic fracture properties for the section size have been used and projected for future use in naval structures. Figure 35 illustrates the general RAD locations of HY-80, HY-100, and projected HY-130 steels. The important point is that the plastic fracture properties for section sizes of at least 3.0-inch (75mm) plate thickness are the basic requirements for limiting cost and ensuring high reliability under explosion-loading attack. The strength limitation is of metallurgical origin; the metals must lie significantly above the ratio 1.5 region of the RAD. The HY-180, high-corridor steels are expected to provide plastic fracture properties for section sizes of 1- to 1.5-inch (25 to 40mm) and elastic-plastic properties for section sizes 3- to 4-inch (75 to 100mm).

Now, the above rationalization is compared to the design range for aircraft structures. This is indicated by the low corridor "boxes" and by the improved metals that now may be used (based on 1970 technology) and are defined by the higher corridors. If the requirements for minimum yield strengths of at least 200 ksi (140 kg/mm^2) must be met, then metal of plane-strain fracture properties must be accepted for section sizes of 1.0 inch (25mm). As the section size decreases, elastic-plastic properties become available in this high strength range.

The purpose of these comparisons is to emphasize that the <u>strength dividing line</u> is very narrow between flaw-tolerant metal and highly flaw-sensitive metal. This dividing line, for section sizes of 1.0 inch (25mm), lies in the 190 to 210 ksi (133 to 147 kg/mm^2) yield strength range and is <u>inherent</u> to metallurgical factors. Also, it defines a sharp demarcation between low-cost and high-cost fabrication as well as simple

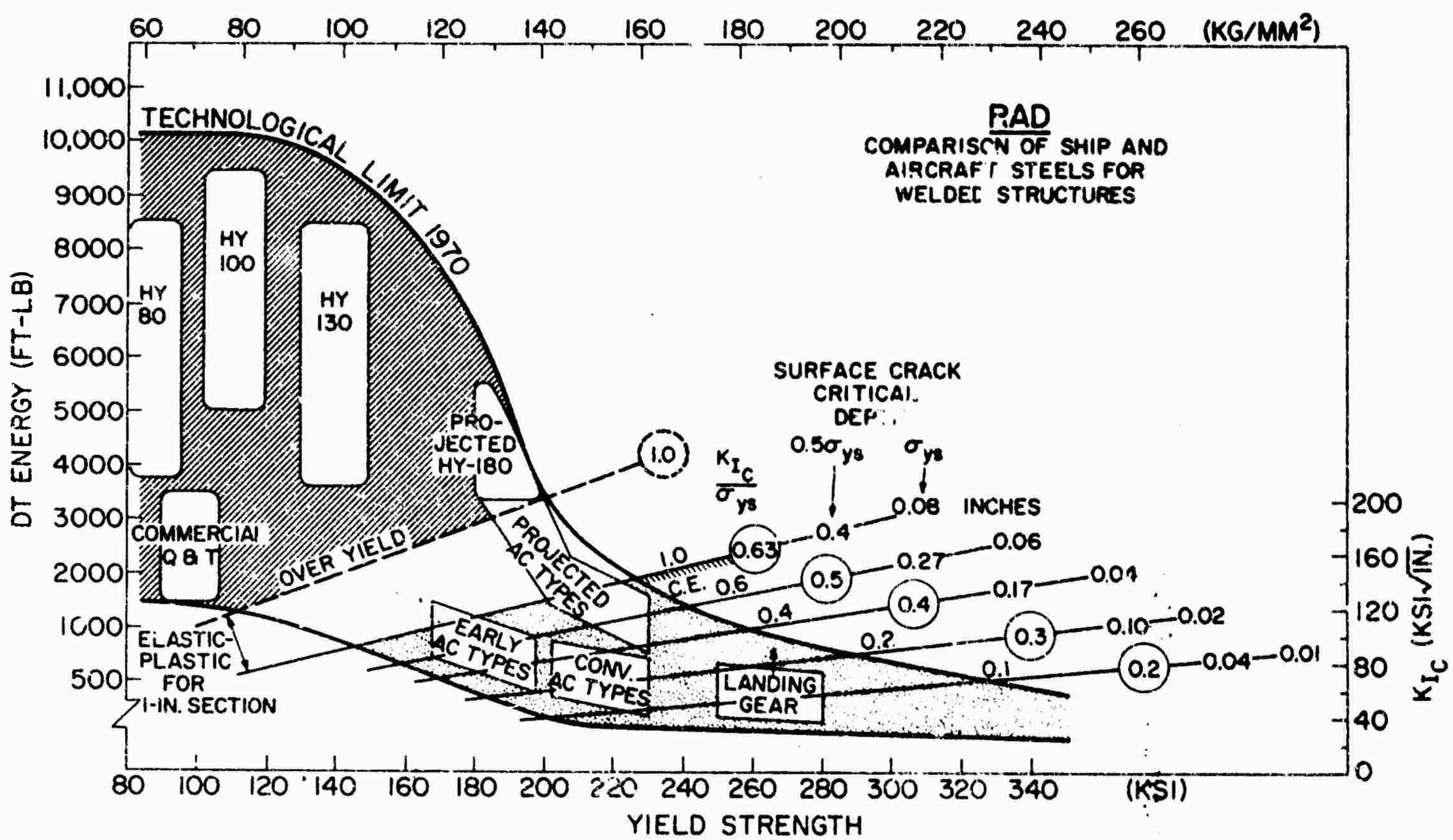

FIGURE 35. RAD Spectrum of Generic Steels Used in Welded Fabrication. Note that the trends for ship steels have been from HY-80 to HY-100, HY-130 and toward HY-180. The trends for aircraft steels have been from the early, to conventional, and then (expected) to the highest-corridor, with modest decreases in yield strength. Thus, there is a meeting of the two types at the 180 to 220 ksi (125 to 155 kg/mm^2), ratio 0.8 to 1.0, interface location -- evolving from the two trends.

Source: Naval Research Laboratory.

and complex inspection requirements. The metallurgical "transition" range is all determining for these various aspects.

Costs for metal testing, inspection, and quality control must rise sharply in dropping through the elastic-plastic transition to the plane-strain state for the section size. For example, refer to Figure 31 and consider the new premium metals "chain." Assume a section size in the structure of 1.0 inch (25mm).

The subject costs should be relatively low as the maximum yield strength is increased to approximately 200 ksi (140 kg/mm^2). Above this level, the plane-strain region is entered for this section size. The lower bound values of the statistical box will determine the K_{Ic} value that must be used in specifications and design.

The cost curve should show a <u>sharp</u> <u>rise</u> in the range of 200 to 230 ksi (140 to 160 kg/mm^2). This is the cost barrier, which determines the yield strength limits for nonredundant components (single load path). If inspection for critical flaws is a contractual requirement, the cost curve becomes a pragmatic consideration in design. This is <u>not</u> a metals-cost curve. It is a fabrication and quality control cost-curve.

10. <u>Titanium and Aluminum Alloys</u>

The RAD summarizations of commercial titanium and aluminum alloys are presented in Figures 36 and 37. The significance of the ratio lines is exactly the same as for steels, because fracture-mechanics definitions of fracture properties are not dependent on metal type.

The metallurgical transition from high to low levels of fracture resistance is (as for steels) strength related and may be modified considerably by metal-quality factors.

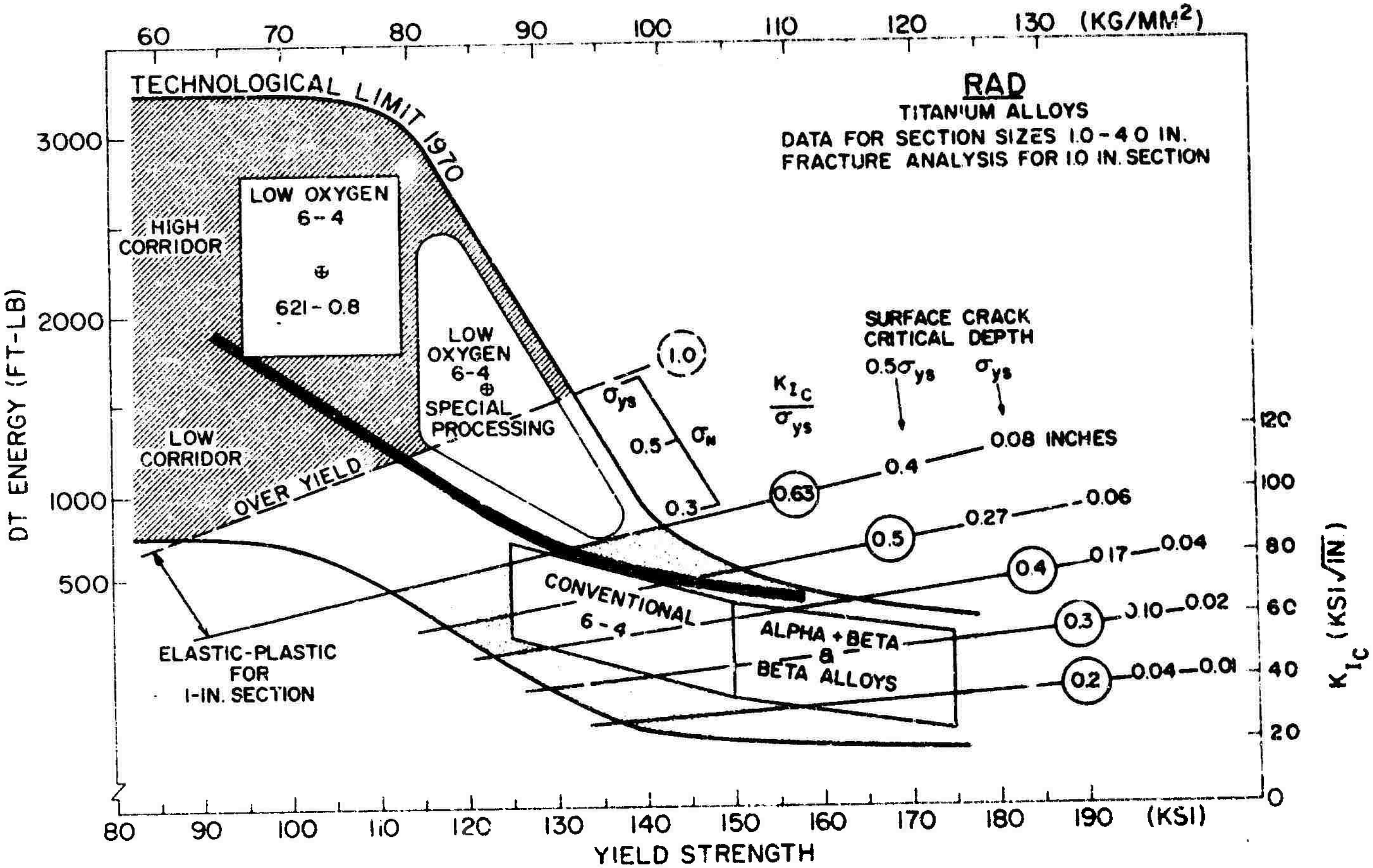

FIGURE 36. RAD for Titanium Alloys, as Prepared for Trade-off Analyses Involving Plate of 1.0-in. (25 mm) Section Size. The metallurgical zoning provides for metal selection, depending on structural requirements. For example, at 120 to 130 ksi (85 to 92 kg/mm^2) yield strength, a choice may be made for a specific alloy, featuring two levels of oxygen content. The properties are vastly different -- plane strain versus plastic fracture-states.

Source: Naval Research Laboratory.

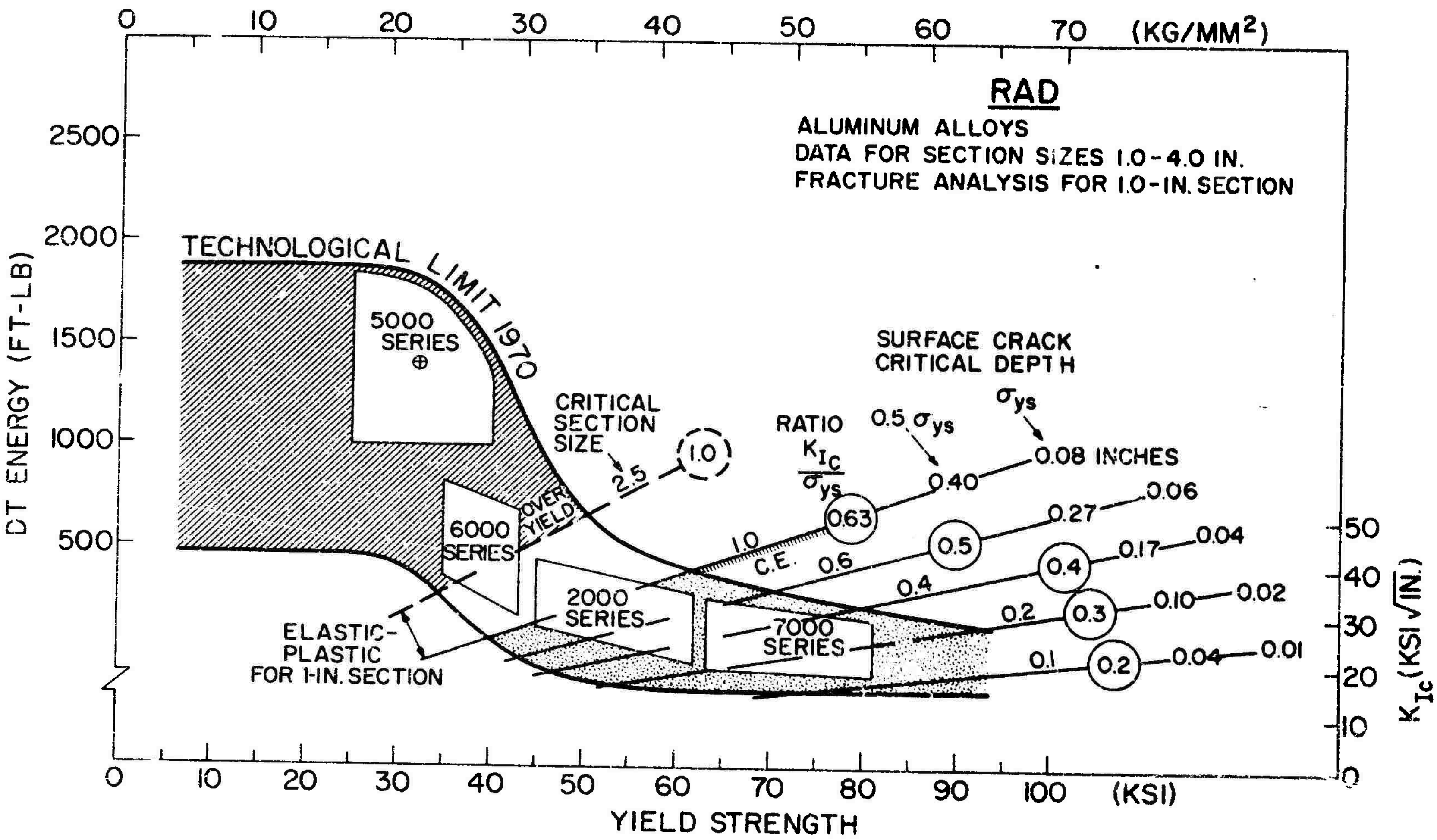

FIGURE 37. RAD for Aluminum Alloys, as Prepared for Trade-off Analyses Involving Plate of 1.0-in. (25 mm) Section Size.

Source: Naval Research Laboratory.

The primary metal-quality factor for titanium alloys is oxygen content because this metal is ordinarily "highly clean" due to vacuum-arc melting production practices. The metallurgical "problem" is to avoid embrittling effects due to oxygen. The use of oxygen in small amounts to promote increased strengthening in the 120 to 140 ksi (85 to 100 kg/mm^2) yield strength range is catastrophic to fracture resistance. The "boxes" in Figure 37 illustrate the expected fracture properties of titanium alloys produced to conventional commercial purity (C.P.) oxygen levels compared to low oxygen (less than 0.10 percent) alloys of slightly lower yield strength.

A special note should be made of the combined effects resulting from decreases of 10 ksi (7 kg/mm^2) in minimum yield strength, 155 versus 125 ksi (80 versus 87 kg/mm^2) and using low oxygen metal. Section sizes of 1.0 inch (25mm) will show constraint transitions from plane-strain to elastic-plastic (or better) material, as the result of these combined changes and as may be deduced from Figure 36.

The dashed line represents the boundary between conventional (present production) metal of C.P. grade and the new low-oxygen metal. The span between the dashed line and the 1970 technological limit represents the improvements that have been identified since 1968. There are sound metallurgical reasons for believing that additional improvements may be made by control of texture and microstructure. Heat treatment and metal-processing factors are particularly important for titanium alloys and, as yet, are explored only partly. This is particularly true for section sizes in the order of 3.0 inch (75mm).

The RAD for aluminum alloys is presented in Figure 37. The effects of increased strength level on decrease in fracture resistance are again evident. In this case, it is not possible to present a "prior" versus a 1970 technological limit. No significant improvement in these respects has been recorded to date.

Aluminum alloys are metallurgically "dirty" in the sense that vast amounts of brittle intermetallic compounds are present to serve as initiation sites for microcracking and voids. Accordingly, the true potential of aluminum alloys is not apparent. Deliberate research should be aimed at this significant concept. Reporting now must be limited to, and should be accepted for, energy-measurement procedures. Such measurements are scientifically defensible as being adequate for defining elastic-plastic and plastic fracture properties.

Analytical treatment of the elastic-plastic case remains for the future. The J-integral approach is cited as a logical procedure, based on present knowledge. When the analytical procedures mature, it may be possible to calculate critical crack sizes for the elastic-plastic regions of the RAD. This may permit extending the critical crack-size scale to above the ratio-line limit of the section size. It should not change the basic analyses presented herein.

A low cost test, such as the DT, can be used to "screen" metal quality at the ingot (or later) stages. The costs of using K_{Ic} specimens of over 2.0-inch (50mm) size for defining over-0.63 ratio values are very high. Cost is the true value of the DT test energy-scale relationship to the grid system. Moreover, DT testing does not result in reporting "no-test"

(K_{Ic} cannot be measured) values, and a test reading is always significant.

The critical-edge concept defines highly significant improvement in metal properties that may be made over the region of the "strength transition." This is the region of rapid fall-off of the RAD plot for each metal system. The highly significant improvement must be related to specific section sizes. Thus, the improvement possibilities must be limited to lower yield-strength ranges for thick-section metal. With decrease in section size, higher yield-strength ranges provide the improvement challenge.

The degree to which these studies may be fruitful depends on the investigations to date on the various strength ranges of steel, titanium, and aluminum alloys. In general, steels have been investigated extensively and led to the detailed analyses of metallurgical factors discussed herein. Titanium alloys have not been investigated adequately. In conclusion, metal-improvement studies are needed mostly for aluminum and titanium alloys, and lastly for steels.

Conversely, the benefits to be derived from present use of the technologically limited metals may be very high for both steels and titanium alloys. These "new" metals of premium quality offer elastic-plastic properties at strength levels for which the commercial grades of present warehouse stock would provide only low level plane-strain fracture properties.

For weld metal, there is equal need for investigating effects of new technological improvements that result from advances in inert-arc, electron-beam, and the newly emerging laser-beam welding methods. Data availability, systematization

of strength-related trends, and consequent analyses of properties are poorly developed for all three weld-metal systems at this time.

11. Conclusions

Projections of potential improvement in the fracture properties of high-strength metals can be evolved only from a base of sound scientific and technological assessments of past directions and present status. Analytical capabilities for such assessments have been developed largely since 1968, and most notably since 1970. During this period, sufficient data became available for the first time for detailed analyses of metallurgical and mechanical factors over a broad range of strength levels.

Most importantly, studies of metallurgical factors for steels deviated from the traditional focus on microstructure (physical metallurgy) and included cleanliness aspects (process metallurgy). These studies were possible when commercial facilities became available for vacuum melting, vacuum deoxidation, and vacuum-arc remelting.

Thus, steels of relatively thick section size, 1.0 to 4.0 inch (25 to 100mm) could be produced for investigation of mechanical-constraint relationships to metallurgical quality. The other important variable, strength level, was investigated by heat-treating these plates over the critical range of the strength transition, i.e., 160 to 220 ksi (110 to 155 kg/mm^2) yield strength. The three independent factors (mechanical constraint, metal quality, and yield-strength level) must be analyzed simultaneously to summarize present technological limits and to project potential shifting of these limits to higher strength levels. Varying only one or two of these factors cannot provide adequate answers to questions of fracture properties.

Constraint level is the basic mechanical-state reference; strength level is the primary engineering reference; and cleanliness quality is one of the most critical metallurgical references. The measured value of fracture properties is the result of interactions between these three factors.

The "common denominator" for simultaneous analysis of these inter-relationships is the K_{Ic}/σ_{ys} parameter, which serves the dual role of characterizing metal properties and interpreting their fracture-state properties.

The Ratio Analysis Diagram (RAD) evolved on this premise and uses a K_{Ic}/σ_{ys} ratio-line grid for the mechanical analysis of metal K_{Ic}/σ_{ys} ratio properties. Metallurgical zoning of the RAD records behavioral trends with respect to metal-quality factors. In simple terms, behavioral trends that result in intrinsic changes of metal K_{Ic}/σ_{ys} properties will cause "shifts" across the K_{Ic}/σ_{ys} grid and will result in definable fracture-state transitions for specified section sizes.

The analyses of RAD-defined behavioral trends lead to the following conclusions:

a. Increasing strength generally causes a decrease in fracture resistance from plastic to elastic-plastic and then to plane-strain states. This effect is defined as the "strength transition," i.e., a strength-induced transition. It is made evident by plotting fracture-state properties against a scale of increasing yield strength.

b. The general shape of strength-induced transition curves involves an upper plateau region (full plastic state) and a lower plateau region (low

level plane-strain state), connected by an intermediate region of sharply falling fracture resistance. The elastic-plastic state lies in the center of this sharply falling region.

c. All metals feature an <u>intrinsic</u> "quality" for resisting the incubation and growth of microvoids as the grain structure is subjected to plastic flow at crack tips. The quality aspect is cleanliness, i.e., the relative concentration of nonmetallic phases "foreign" to the metal-grain structure. Reduction in the number of sites that promote microseparations of the metal grains results in increased fracture resistance.

d. Cleanliness quality is decided at the time of ingot solidification. Forging or heat-treatment effects can influence fracture properties for a specified strength only to ceiling levels dictated by metal-quality factors.

e. Steels feature three quality corridors of strength-induced transitions that correspond to: (1) relatively poor, (2) intermediate, and (3) high levels of cleanliness. The strength-induced transition in fracture states for low corridor-quality metals evolves at the lowest yield strength range; for intermediate quality metal, it evolves at a distinctly higher yield-strength range; and for highest quality metal, it evolves at the highest possible yield-strength range.

f. The fracture-state transitions, which evolve <u>within</u> each of these metal-quality corridors, are section

size dependent for mechanical constraint reasons. Thus, there is a shift to lower yield strengths (within the corridor) for the fracture-state transitions of thick-section metals and to higher yield strength levels for the fracture-state transitions of thin-section metals.

g. The effects of metallurgical improvements that result in increasing fracture resistance while remaining in the plane-strain state of a specified section-size (K_{Ic} can be measured) are interpretable in terms of critical crack sizes. The interpretations include consideration of the relative stress level acting on the assumed crack. In general, there is small benefit from merely increasing the K_{Ic} value, if stress levels are high.

h. High returns for metallurgical improvements are indicated by "critical-edge analyses." The critical-edge index is the K_{Ic}/σ_{ys} ratio limit for the section size. Improvements that elevate the metal from this plane-strain limit (past the critical edge) to elastic-plastic fracture are highly significant because they imply large increases in critical crack sizes for regions of high as well as low relative stress.

i. The highest possible strength levels for improvements of critical-edge type (elevation from plane-strain to the elastic-plastic states) are attained by the use of metals of highest corridor-quality features. The specific strength level of critical-edge improvement is determined by the section size within the limits established by the corridor quality.

j. If a minimum level of fracture properties (K_{Ic} or elastic-plastic) is specified, then a yield-strength limitation must be accepted. Conversely, if a minimum yield strength is specified, then it is necessary to accept a fracture-properties limitation. The trade offs between these "choices" are made evident by the RAD plot. Metal-quality improvements simply provide for specification of the highest possible strength versus fracture-toughness combinations within attainable limits.

k. Metallurgical variance factors must be considered in analyses of maximum attainable fracture properties for minimum specified values of yield strength. In general, a yield-strength range of 20 to 30 ksi (15 to 20 kg/mm^2) above the specified minimum value must be accepted for ordinary production practices. The inverse relationship with fracture properties signifies that the higher strength metal of the population will feature statistically lower levels of fracture resistance compared to the lower strength metal of the population. Thus, the higher strength metal of the population determines the highest level of fracture resistance that can be specified.

l. The "statistical box" aspects of these relationships between strength and fracture may be plotted in the RAD with due consideration of the quality corridor within which the metal resides. Thus, specification values that lead to high rejection rates can be identified a priori as well as values that lead to minimum rejection for any level of designated

minimum yield strength. In particular, these plots provide assessment of the validity of producer-offered guarantee values, that is, whether these are realistic, unrealistic, low, etc., as compared to the statistical expectancy for the quality-corridor feature of the metal.

m. Extensive investigations for steels have identified melting and processing procedures that produce three corridor levels. The highest corridor represents premium quality metal. Relatively, there is limited expectation for improvements of major scope, i.e., to a higher (fourth) corridor. The best properties expected for specific conditions of constraint (section size) are identifiable. Use should be made of these premium metals, evolved since 1968.

n. Reasonably extensive investigations have been made of titanium alloys. Two metal-quality corridors are identified. There are reasonable expectations that a third (higher) corridor quality may evolve by studies of processing factors. However, use should be made of these premium-quality materials (of second corridor level) featuring low-oxygen contents.

o. Aluminum alloys have not been investigated adequately as to metal-quality factors. In effect, the aluminum alloys are limited to one low-quality corridor. There are strong expectations that studies, similar to those for steels, should evolve metals of intermediate and high corridor features.

p. These assessments for metal-improvement expectancy serve as recommendations that priority of further

research effort be placed on: (1) titanium alloys due to their critical importance to advanced aircraft, (2) aluminum alloys due to their neglected state, and (3) steels due to their advanced technological status.

q. These recommendations do not include welds. In this respect, all three metal systems should be investigated with equal emphasis. In particular, the additional technological advances that may be made for inert atmosphere (shielded gas) welding should be compared to the potentials of electron beam and the newly emerging laser-beam welding procedures. Weld-metal properties also may be separated into metal-quality corridors. However, only a rudimentary start has been made in such a systematization of data.

12. Cyclic Crack Growth

a. Discussion

The metallurgical problem presented by cyclic crack growth is illustrated in Table 6 that compares the resistance to cyclic growth of a wide range of materials.* The table reveals that the resistance to growth is roughly proportional to Young's modulus (E) but virtually insensitive to large changes in the yield strength (Y). Yet, the design stresses and ΔK-levels, encountered in service, are roughly proportional to Y. The net result is that the cyclic life, N, can be expected to fall exponentially with increases in the yield strength $N \propto Y^{(1-m)}$, where $m \sim 3$-4 is the exponent that appears in the $\frac{da}{dn}\Delta K$ relation. Accordingly a threefold increase in yield

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* $\Delta K_{10^{-5}}$ is defined as the stress-intensity range that produces a crack-growth rate of 10^{-5} in/cycle.

TABLE 6. Summary of Selected Cyclic Crack Growth Resistance Values for a Growth Rate $\frac{da}{dN} = 10^{-5}$ In.

MATERIAL	Y (Ksi)	$\Delta K_{10^{-5}}$ (Ksi$\sqrt{in}$)	$\frac{\Delta K_{10^{-5}}}{E}$ $10^{-3}\sqrt{in}$	A'	ΔK_{I_c} (Ksi$\sqrt{in}$)	REFERENCE
Fe-3Si	64	~30	1.3	6.2	-	Present Study
3Ni-Mo-V	93	30	1.3	5.9	-	Bates and Clark, 1969
HY-80	95	33	1.1	8.3	-	Barsom, et al., 1968
HY-130	140	28.5	1.0	10.3	92	Barsom, et al., 1968
4340 (Q & T at 1000°F)	183	33	1.1	8.3	80	Miller, 1961
10Ni-Cr-Mo-Co	181	36	1.2	7.4	86	Barsom, et al., 1968
18Ni-Maraging	218	31	1.0	8.4	80	Miller, 1961
18Ni-Maraging	240/262	36	1.2	7.9	80	Wei, et al., 1971; and Carman and Katlin, 1966
H11	242	34	1.1	7.9	-	Carman and Katlin, 1966
D6AC	241	32	1.1	8.8	~70	Carman and Katlin, 1966
				Avg. 7.9		
5456-H321	37	12	1.2	7.0	-	Bates and Clark, 1969
2024-T3	50	9.5/13	1.0/1.3	11/ 5.9	29	Forman, et al., 1966; Donaldson and Anderson, 1967; McEvily and Illg, 1958; and Hudson and Hardrath, 1961 Weibull, 1954
2024-T3	50	13.5	1.1	9.1	16	Broek and Schijve, 1963
2024-T3	50	14	1.4	5.1	-	Broek, 1969
7075-T6	70	10	1.0	10.0	20	Broek, 1969
7075-T6 (Argon)	70	14.5	1.5	4.9	-	Wei and Landes, 1969
7075-T6	70	7.5	0.9	17.8	22	Wei and Landes, 1969
7079-T6	65	12	1.2	7.0	-	Bates and Clark, 1969
				Avg. 9.3		
Ti-6Al-4V	127	15	0.9	11.4	-	Bates and Clark, 1969
70-30 Brass	18	14	0.9	13.0	-	McEvily, et al., 1965
70-30 Brass	92	14	0.9	13.0	-	McEvily, et al., 1965

$\Delta K_{10^{-5}} \equiv \Delta K @ \frac{da}{dN} = 10^{-5}$ in

$$A' \equiv 10^{-5} \left(\frac{\Delta K_{10^{-5}}}{E} \right)^{-2}$$

Y - Yield Strength

E - Young's Modulus

Source: Hahn et al., 1969

strength is accompanied by a ten- to twentyfold reduction in the cyclic life, assuming the initial flaw size and environmental sensitivity are unchanged. This reduction in cyclic life can become a limiting factor in the exploitation of high-strength alloys. Clearly, alloy-development efforts must seek to match increases in strength with improvements in the cyclic growth resistance.

In comparison to the resources that have been spent improving the yield strength of alloys, cyclic growth resistance has received little attention. Even plans for achieving significant improvements are ill defined, as illustrated by the following findings:

1) Cyclic crack growth may result from contributing processes that are controlled by different metallurgical variables and include: (a) cyclic plastic deformation and attending instabilities, (b) corrosion processes; (c) cleavage; and (d) rupture of hard particles.
2) The usual microstructural alterations that affect the yield strength do not have a marked influence on these processes (see Table 3).
3) Additions of 13.5 percent aluminum to copper have indicated that the cyclic crack growth rate is reduced tenfold, see Figure 38 (Miller, et al., 1966; Ishii, and Weertman, 1971). In this case, the aluminum additions probably affect the cyclic flow by way of the stacking fault energy.
4) Averaging combined with a higher copper content and Zn/Mg ratio enhance the cyclic life of 7000-series alloys immersed in 3.5 percent NaCl solution by as much as 50 to 100 percent (Hyatt and Quist, 1969).

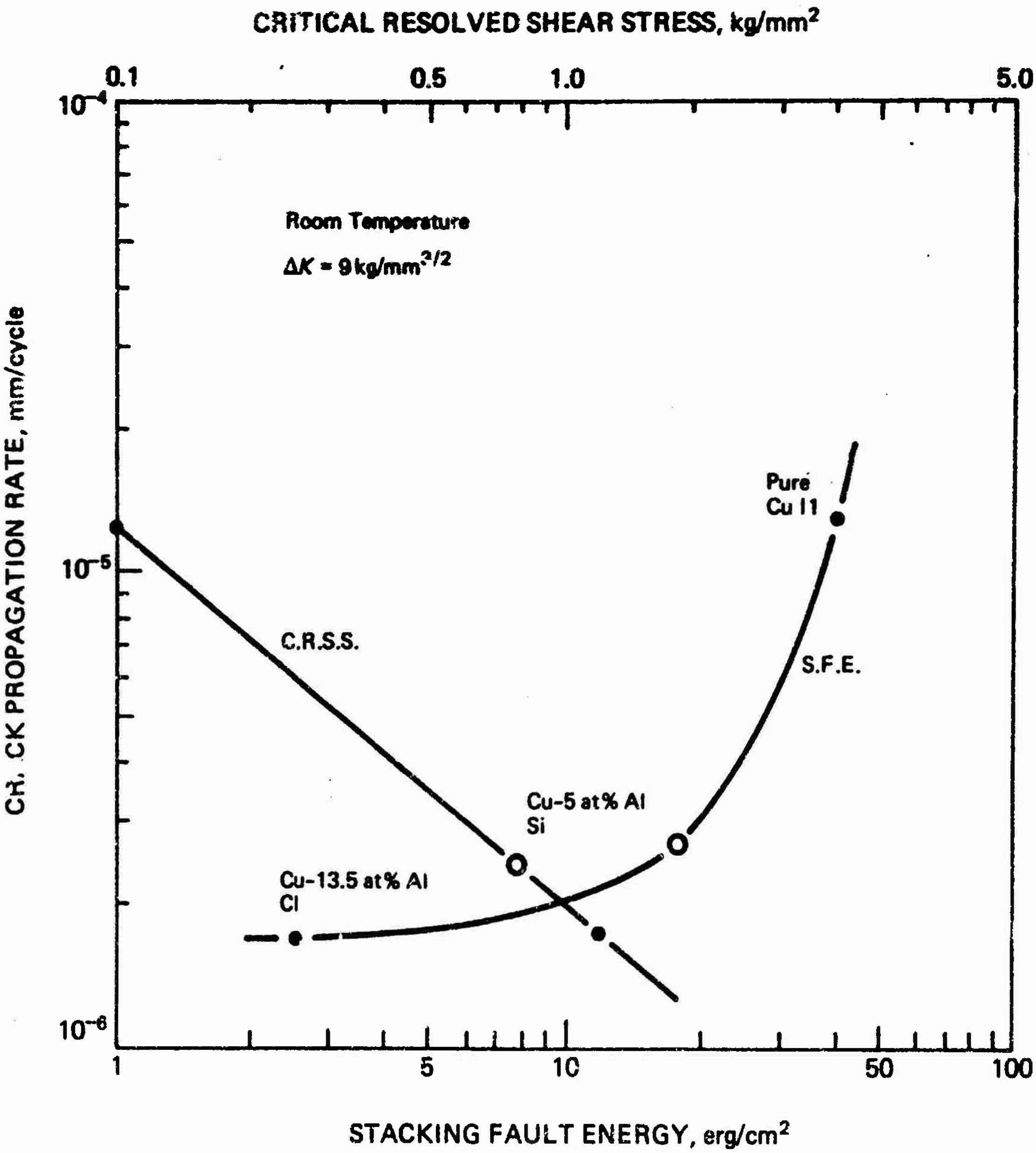

FIGURE 38. Influence of Aluminum Content and Stacking Fault Energy on the Cyclic Crack Growth Rate in Copper Crystals.

Source: Miller et al., 1966; and Ishii and Weertman, 1971.

5) Refining the grain size reduces cyclic growth in Fe-3Si alloy by inhibiting cleavage (Hahn, et al., 1971).

6) Demonstrated two- to fourfold reductions in the cyclic growth rate in high-purity Ni-Cr-Mo steels have been identified normally with the absence of embrittled grain boundaries (Evans, et al., 1971).

7) Other workers have found that $\frac{da}{dn}$, the macroscopic growth rate, can be two to three times greater than the striation spacing and attribute the discrepancy to the rupture of extraneous hard particles and inclusions in advance of the main crack (Pelloux, 1964; Broek, 1969; Bates and Clack, 1969).

b. Recommendation

More research is needed to establish the mechanisms of cyclic crack growth, particularly in service environments, to understand the influence of metallurgical factors so that alloys and processing schedules may be improved.

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